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**OPTIMISATION OF FRAMED CHILD RESTRAINTS**

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MAY 1994

A THESIS SUBMITTED FOR THE DEGREE OF  
DOCTOR OF PHILOSOPHY

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ROAD SAFETY ENGINEERING LABORATORY  
SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

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## ABSTRACT

This thesis documents a study into the effects of various parameters on the performance of Framed Child Seats (FCS) for automobiles. The work investigated the effect of three different sets of parameters:

- FCS design parameters
- Vehicle design parameters
- Occupant biomechanical parameters

The work was conducted at Middlesex University using a combination of experimental crash testing and computerised crash simulations. The experimental crash tests were conducted using the Road Safety Engineering Laboratory, Middlesex University impact test rig and the computerised simulations were conducted using MADYMO3D software.

The performance of the FCS configuration was assessed in terms of the potential injury to a child occupant in a 50 km/h frontal impact to ECE R44 test specification.

All the FCS design parameters examined were shown to have a potential effect on the performance of the FCS. In particular FCS footprint area was shown in the experimental tests to have a significant affect on the performance. A large flat footprint was observed to reduce chest acceleration by 33%, although this was at the expense of a large increase in forward head excursion.

Various vehicle design parameters were shown, by MADYMO3D simulation, to have a considerable affect on FCS performance. A standardised semi-rigid or rigid anchorage system is recommended to overcome such problems in real vehicles.

The biomechanical work was largely based around the potential for injury to the occupant's neck. An improved MADYMO3D representation of the dummy neck was developed for this work and several factors were examined. Chin-chest contact, head mass and neck fulcrum for bending were all shown to have a potential affect on the likelihood of injury.

Limitations of both experimental crash testing and computerised simulations were identified during this work and are discussed in this thesis.



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## PREFACE

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## AUTHORS DECLARATION

Some of the work that is documented within this thesis has been presented elsewhere by the author or co-written with the author. All of the work was conducted by the author.

The initial experimental work was conducted on behalf of the Transport Research Laboratory and is documented in a contractors report: Dorn & Roy (1990). This work also form the basis for a paper which was included in the proceedings of the 13<sup>th</sup> International Technical Conference on Experimental Safety Vehicles, Paris: Dorn, Roy & Lowne (1991).

Part of the MADYMO 3D crash victim simulation was presented by the author at the 3<sup>rd</sup> International MADYMO Users' Meeting, Detroit: Dorn (1992).

This work was conducted between September 1989 and August 1992 whilst the author was employed at Middlesex University. The author has since been in full-time employment and has completed writing this thesis within his own time. As such it is recognised that the Literature Survey is likely to be mildly out of date. Unfortunately, it was not possible to rectify this fault.

## DEFINITIONS

3ms	-	Three Millisecond, refers to a form of peak acceleration evaluation.
CG	-	Centre of Gravity
CR	-	Child Restraint
CVS	-	Crash Victim Simulation
FCS	-	Framed Child Seat
GSI	-	Gadd Severity Index
HIC	-	Head Injury Criterion
IPI	-	Injury Potential Indicator
MADYMO	-	MAThematical DYnamic MOdel - CVS package produced by TNO, The Netherlands
MOI	-	Moment of Inertia
RSEL	-	Road Safety Engineering Laboratory (Middlesex University)
TRL	-	Transport Research Laboratory, Formerly the Transport and Road Research Laboratory (TRRL). (Dept of Transport, UK)

## 1 INTRODUCTION

## 1 INTRODUCTION

Child Restraints (CR) provide invaluable protection for children involved in automotive accidents. It is not the purpose of this thesis to dispute the effectiveness of child restraints themselves, but to examine and quantify the problems of CR when used in real vehicles. It is hoped that the information contained in this document can be used to improve the safety of children in cars.

Perhaps the first question that should be addressed in this document is "Why are child restraints necessary?". This question can be answered in two ways; the first revolves around the particular anatomical differences between children and adults, whereas a second answer could be in the form of an evaluation of the effectiveness of child restraints from the injury statistics.

The former answer was first put forward by Burdi et al in 1969. Up to that date, many child restraints were designed purely as a comfortable seat for the child during transit and they offered little or no injury protection. Occupant protection for a child was only really available by use of the adult seat belt. Burdi described in plain English the anatomical differences between children and adults and was the first to really point out that ".....infants and children are not miniature adults". The body proportions and skeletal development of a child are so different to the adult that a standard or even scaled down seat belt is not suitable as a child restraint. One of the most important of these features is the pelvic development. The iliac crests in the adult are used as an adult lap belt locator, i.e. the lap belt is designed to hook under the ilium during impact. This reduces the likelihood of the occupant sliding under the belt (an occurrence

which is generally termed submarining). This locating of the lap belt can not occur on a young child as the iliac crests do not fully form until the age of 10 years (see Burdi et al 1969). Thus a five point harness is required to adequately restrain a young child. The five point harness comprises; two shoulder straps, a lap belt and a crotch strap. The crotch strap is designed to hold the lap belt down in position on the pelvis and thus reduce the occurrence of submarining. It is not designed to directly load genital area of the occupant's body.

The second method of answering the question "Why are child restraints necessary ?", is to look at the injury statistics for restrained and unrestrained children. The Swedish injury experience was summarised by Turbell (1989). The risk of a child being injured in a road accident was calculated from injury data and is shown in Table 1.i.

**Table 1.i Child injury risk in Sweden, from Turbell (1989)**

Method of Restraint	Injury Risk %
Unrestrained	15.6
Adult Belt Only	8.9
Forward Facing Child Restraint	6.9
Rearward Facing Child Restraint	1.2

The Swedish data includes all accidents, however minor, and thus the injury risk for unrestrained children is quite small. Nevertheless the potential for reduction in injury of a child restraint can be seen. Adult belts are shown to reduce the risk of injury, but not to the level of child restraints.



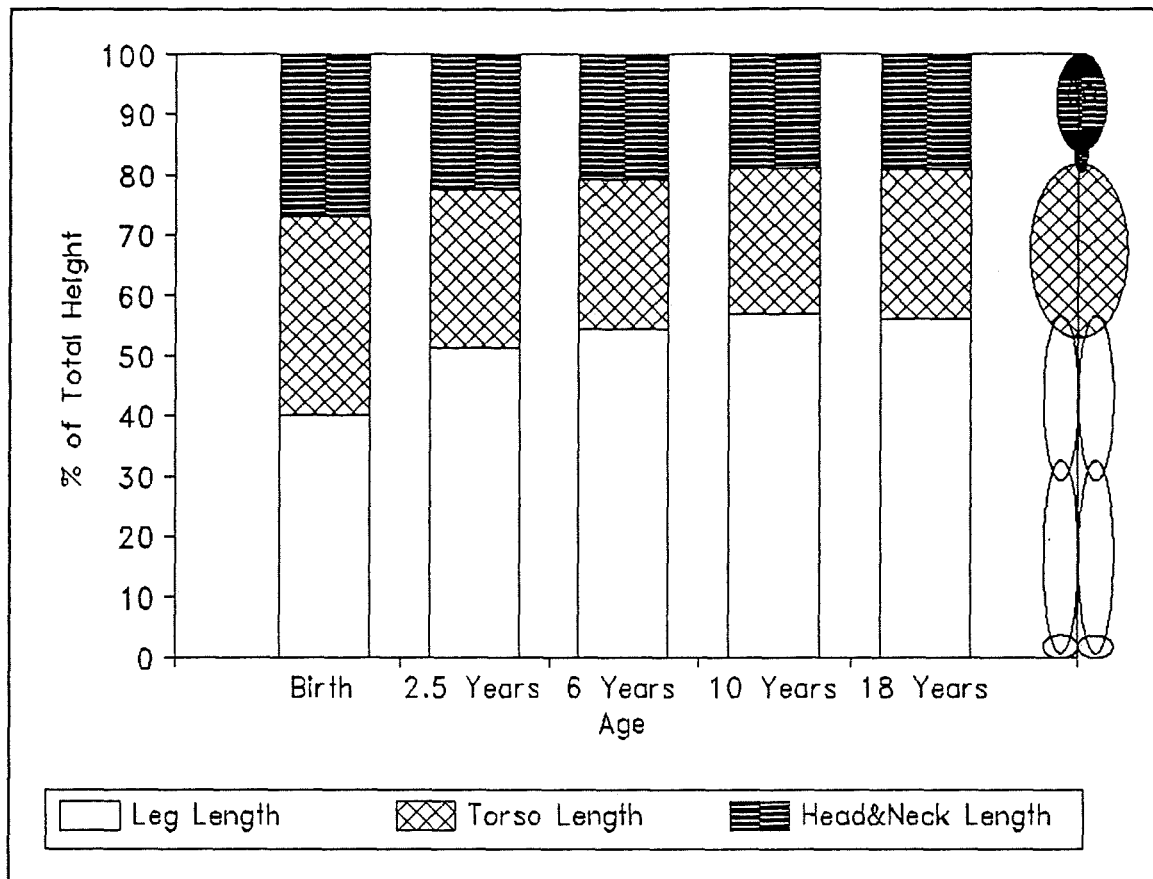
The results of a similar study in Germany are shown in Table 1.ii.

**Table 1.ii** German injury data, taken from Langweider and Thummel (1989)

MAIS Distribution				
MAIS	Unrestrained %		Restrained %	
0	48.6	Overall 51.4% Injured	83.6	Overall 17.3% Injured
1	41.3		15.9	
2	6.6		0.9	
3	1.7		0.1	
4/5	1.1		0.2	
6	0.7		0.2	
Total	100		100	

This study only considered restrained or unrestrained children, but it can be easily seen that children in restraints are injured far less frequently than those that are unrestrained (51.4% compared with 17.3%). In addition, the pattern of injury is weighted towards the higher end of the MAIS scale in the case of the unrestrained child. The two studies summarised here illustrate the need for purpose built child restraints, in preference to adult belts and no restraint.

A child's body proportions vary considerably during its development (see Figure 1.1), as does the actual anatomic structure. Thus the method of restraint must vary accordingly. This is the reason for the present range of child restraints. The most common types of child restraints, in the UK, fall roughly into 3 categories:



**Figure 1.1** Variation of child body proportions with age.

- (1) Infant Carriers - Rearward facing child seats for the Birth to 9 months age range, which are anchored with the adult seat belt.
- (2) Forward Facing Child Seats - Child seats for the 9 month to 4 year age range which restrain the child with a five point harness. The seat is anchored with the adult seat belt or a fitting kit.
- (3) Booster Seats/Cushions - For the 4 year and above age range. Merely a height adjuster to allow the child to use the adult seat belt. The Booster seat is also now becoming available for the younger child.

In other European countries there is another type of child restraint for the younger child, that is the shield type restraint. The shield restraint is similar in appearance to a booster seat, however the child is not directly restrained by the adult belt. The child's movement is checked by a body block inserted between the adult lap belt and the abdominal area. This type of seat is popular in Germany and to date it appears to be a effective restraint type. However this restraint is not commonly used in the UK.

This thesis is primarily concerned with only one type of child restraint, namely the Framed Child Seat (FCS). The framed child seat is a forward facing restraint and consists of a plastic shell in which the child is seated, within a plastic or metal frame which

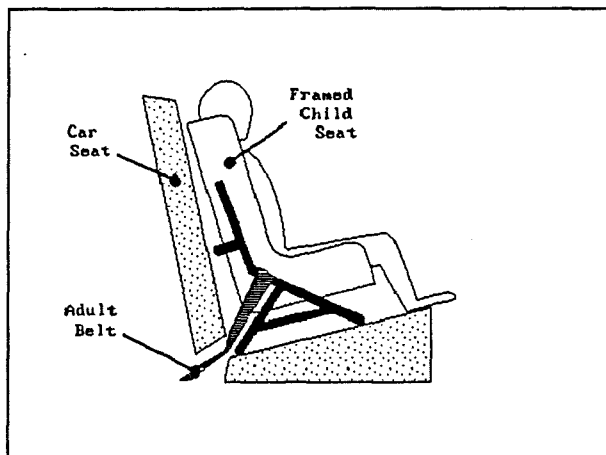


Figure 1.2 Framed Child Seat

rests on the vehicle seat (see Figure 1.2). The child restraint is secured to the vehicle structure using the existing adult seat belt whilst the child is restrained by an integral harness. Since their introduction in the mid 1980's, the framed child seat has become very popular in the UK, all but replacing the original four point child restraint designs. This is due to the ease of installation, low cost and the potential for use in multiple vehicles. The FCS is designed exclusively for the 9 to 18 Kg child mass range (roughly the 9 months to 4 year age range), although some more modern designs can also be used in a rearward facing configuration for infants.

The design of framed child restraints, in the UK, has been largely based around the addition of a frame to existing four point child restraint shells. The four point child restraint consists of the plastic seating shell, which is anchored directly to the vehicle by four retaining straps. Manufacturers used the existing shell design and then added the necessary structure to create the framed child seat. No known work has been published that examines the design of British FCS or the interaction with the vehicle in which they are fitted. Work has been published on the identification of some FCS design parameters which effect the

performance of US (Wismans 1979) and European seats (Janssen 1991). However British child restraints and cars differ substantially in design, and thus these other studies are not necessarily directly applicable.

The main concept of the framed child seat was to make the restraint of children more convenient and simpler. It was hoped that added convenience would lead to the restraint of more child occupants of cars. The simplicity of using the adult seat belt to anchor the restraint was aimed at reducing the misuse which occurs with the original four point anchorage system. However, the design of the child restraints, together with the lack of public education on the correct use of the restraints has meant that misuse of the framed seat does occur.

The performance of FCS must be a function of the restraint itself, the occupant, the car in which it is secured and the means of securing it to the vehicle. Concern over the effectiveness of when used in the 'real world' has been voiced elsewhere. Tarriere (1991) concluded from the study of accident cases that there is a discrepancy between the performance of CR when certificated, and when in a real car crash. However the cause of the discrepancy was not identified or quantified. Thus although it is recognised that the vehicle has an effect on the performance, little work has been published which quantifies the effect.

One of the reasons for alterations in child restraint performance when fitted in cars is the method of standards approval. The standards to which these must adhere (BS 3254:Part2:1988 & ECE R44:1980) test the performance of these restraints fitted to a

standard laboratory test seat, with standard belt anchorages. Car design has altered considerably since these standards were conceived and written, and it is now thought that the test seat used for certification does not now adequately represent the real vehicle seat. Pincemaille et al (1991), pointed out some of the differences between the test and vehicle seats. This problem has to some extent been addressed in the UK, with the impending issue of a modified British Standard (BS3254:Part2:1992). However this author does not consider the modifications to be adequate.

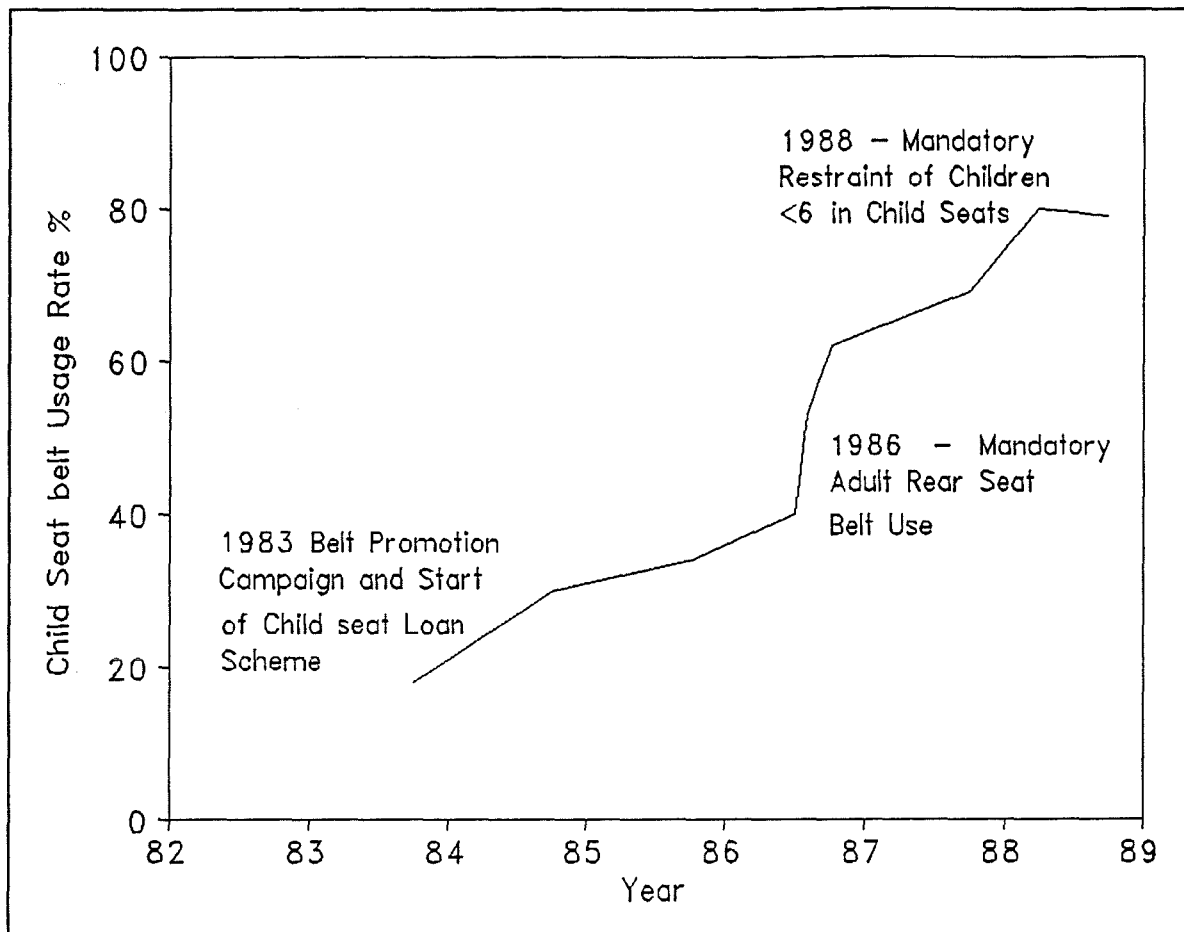
Another reason for the difference in dynamic performance of a child seat when tested and when used in real life, is misuse. Misuse can seriously degrade the performance of a child restraints and affect the perceived effectiveness. For example Vallée et al (1991) found no statistical difference in the fatality rate for restrained and unrestrained children. This was attributed to misuse and the use of unapproved child restraints.

Misuse can take many forms, from not anchoring the child restraint to too large a child for the particular seat. The UK lags behind many countries in the study of misuse, no recent unbiased study has been conducted. Information on the frequency and mode of misuse is essential if manufacturers of child restraints are to improve the designs. A large scale misuse survey of British child restraints is a prerequisite of child seats which prevent misuse. This project did not attempt to address this area of study, however a small sample of UK child restraint misuse is presented, together with a survey of international misuse studies.

Another area of information which still requires considerable

research is child injury tolerance. Most of the injury work that has been conducted to date, has been directed towards adults. This is not to be criticised, as the vast majority of persons who are involved in vehicle impacts are adults. Even with the relatively large amount of work that has been conducted on adult injury, there are still few definitive injury criteria. The problem is that all persons are different, people are different weights, builds and ages and these factors all affect the injury potential. For children this problem is compounded by the differences in anatomy and physiology during a child's development. As mentioned earlier there are many features of a child's body which significantly change during growth and child development can vary significantly between children of the same age. This, compounded by the lack of research in this area, means that there is little knowledge of the injury tolerance of children.

There is another question that will be discussed in this manuscript, which is 'How to get parents to install and use child restraints?'. Methods of persuading parents to install and use child restraints will be reviewed e.g. road safety education, child seat loan schemes, free supply of child seats and legislation (forcing the use of child seats). All of these have been used to great effect in Sweden. Figure 1.3 illustrates the effectiveness of active promotion of restraint use. A dramatic rise in child seat and seat belt use has been observed, firstly when education and loan schemes were initiated in 1983 and secondly with the introduction of legislation in 1986 and 1988. The Swedish legislation, unlike the 1989 British Law, insists that all children must be restrained. And if the child is under 6 years of age the method of restraint must be a designated child

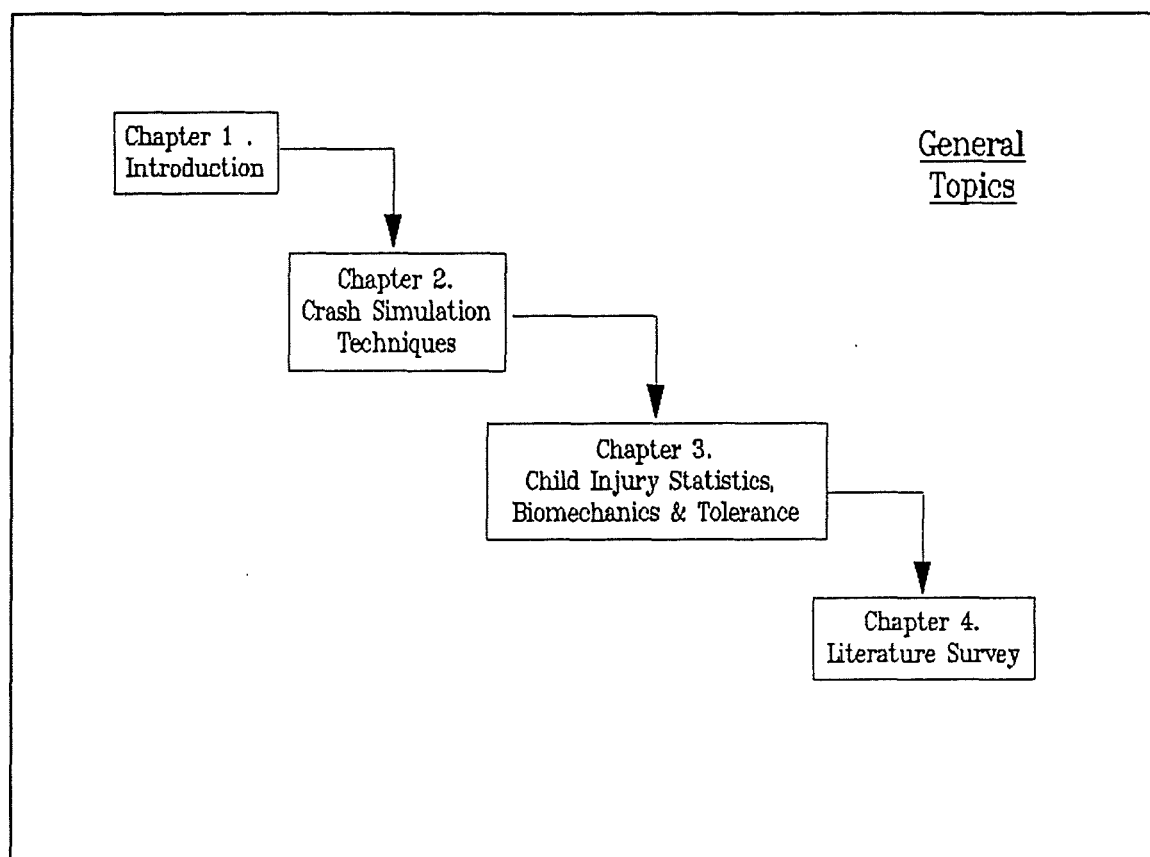


**Figure 1.3** Child seat belt usage rate in Sweden. (Data taken from Turbell - 1989)

restraint system. The British law only insists that the child be restrained, if a suitable restraint is available. This can leave infants unrestrained if no appropriate child restraint is available. There is also a gap in both laws, in that children only need to be restrained in a seating position that has a seat belt. Many children are transported in the older, 'second car' of the family which may not have rear seat belts and thus the children need not be restrained.

This document addresses, or at least touches on, most of the above mentioned points. The initial four chapters provide background information on the subjects of crash simulation, injury biomechanics and other related topics (see Figure 1.4). This includes a literature survey of related work and relevant

international standards for child restraints.



**Figure 1.4** Chapters covering general topics related to FCS

The thesis then continues with the presentation of work conducted to examine the various parameters which affect FCS performance and the injury potential of the child occupant (see Figure 1.5).

Examination of the dynamic performance of the framed child seat, was conducted both by experimental and mathematical models of the car impacts. The experimental work was carried out at the Road Safety Engineering Laboratory, Middlesex University. The mathematical modelling was carried out using a computer software package called MADYMO (MAThematical DYnamic MODEL) which was designed expressly as a Crash Victim Simulator (CVS). Both techniques are described in general (Chapter 2) and then in more detail, specific to work conducted for this thesis, in Chapter 5.



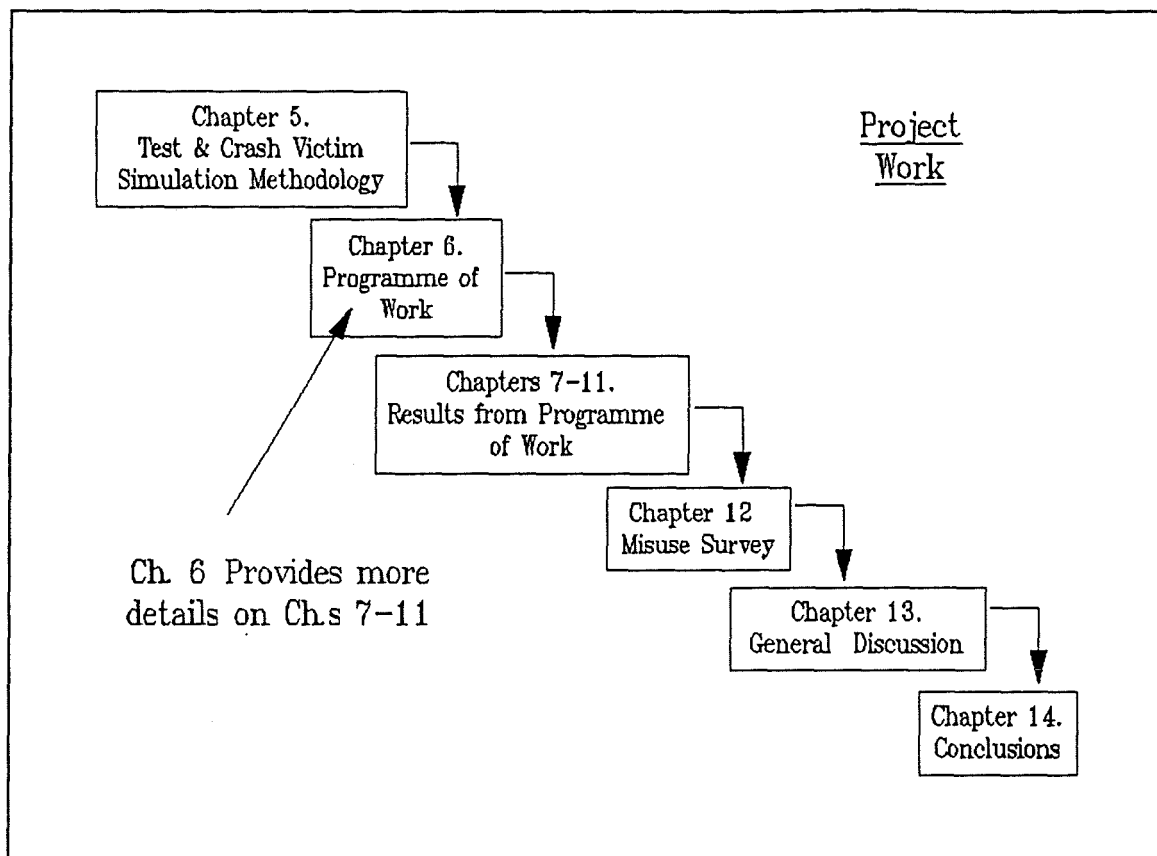


Figure 1.5 Practical work conducted in this project

The results of the investigation into the parameters which affect FCS performance are presented in four chapters. Two dealing with the child seat design parameters and the other two, the vehicle parameters (see Figure 1.6).

A further chapter discusses work which was conducted to investigate some of the parameters effecting injury potential to the child head and neck. This work was conducted using MADYMO3D. It comprised the development of an improved MADYMO representation of the TNO P3 dummy neck and work which examined the effect of some biomechanical features on the injury potential (see Chapter 11).

In addition to crash simulation a limited sample of misuse cases is included as Chapter 12.

The final two chapters draw together the results in a general

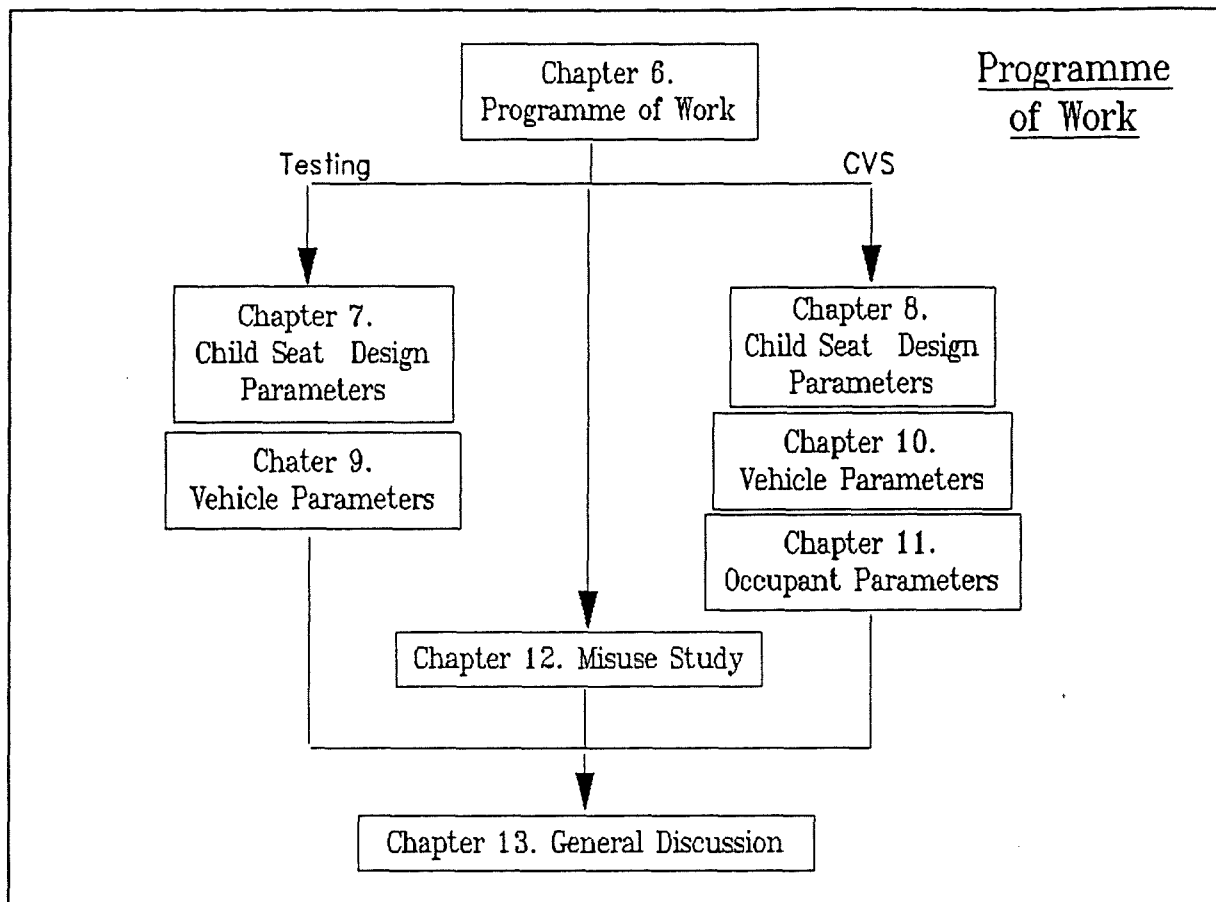


Figure 1.6 Guide to Results Presentation

discussion and present the overall conclusions of the work.

### 1.1 OBJECTIVES

The objectives of this study were as follows:

- ▶ To identify and quantify the effect of:
  - child restraint design
  - vehicle design
  - some occupant parameterson the injury potential to an occupant of a framed child seat.
- ▶ To quantify the extent and the effect of misuse of framed child seats.

## 2 CRASH SIMULATION

## 2 CRASH SIMULATION

In order to assess the performance of an occupant restraint, before it goes on the market, it is appropriate to conduct crash simulation. Static tests of restraints can be conducted and they are valuable as a method of evaluating the strength of a device. However, they can not give any measure of the injury potential to the occupant during a vehicle impact. Once the protection system has been introduced, accident investigation can be conducted to provide data on its performance in actual car impacts. But before the system is introduced, crash simulation is the only method of evaluating the performance.

There are three main crash simulation techniques:

- (a) Vehicle barrier testing.
- (b) Dynamic impact sled testing.
- (c) Mathematical Crash Victim Simulation.

Each of these methods can provide data on the dynamic loading of the vehicle occupant, via the use of human surrogates. However there are limitations on the validity of such simulations due to simplifications of the impact scenario and the representation of the human body. The human occupant is represented by one of three means:

- A cadaver
- An animal surrogate
- A mechanical surrogate (dummy)

Cadavers are the most humanlike surrogate, but they are difficult to obtain in large numbers, are often old or injured specimens, vary greatly in size and do not have the same physiology as a live human (muscle tone, blood pressure etc are lost on death). Animal surrogates can be tested whilst alive, but they are not the same size or have the same anatomy as humans. A mechanical

surrogate can be manufactured in large quantities to close engineering tolerances and be based upon any size of human. Thus they can provide a ready supply of test specimens which will all produce the same dynamic response to the same input. However it is very difficult to design a mechanical surrogate to respond in a humanlike way. Thus there are limitations on each technique.

The three methods of crash simulation will be discussed in this chapter. Emphasis will be placed on the latter two, as these were the methods used in this research project.

### 2.1 VEHICLE BARRIER TESTING

This method of testing involves the impacting of actual manufactured vehicles and thus it is the most realistic of the crash simulations. Vehicle barrier tests can be used to assess the integrity of the vehicle's crashworthiness, the occupant restraints or the total safety package.

There are three vehicle barrier test configurations:

- (a) Vehicle impact with rigid barrier.
- (b) Vehicle impact with movable barrier.
- (c) Vehicle to Vehicle impact.

In each configuration the striking vehicle (or movable barrier) is accelerated up to speed (generally by a winch) and impacts with the struck object. The vehicles can contain a full "family" of dummies (human surrogates) which are instrumented with transducers to measure accelerations, loads and displacements. In addition the impact is generally recorded on high speed film, so that displacement measurements and analysis can be made post-test.

Although this is the most realistic crash simulation, it is not widely used for occupant restraint evaluation. A large expense is incurred in the vehicle cost, a new vehicle (or two) is required for each test. There is also a greater problem with test repeatability, due to the difficulty in arranging for the vehicle (or vehicles) to impact at the correct velocity, angle and position. There are many other disadvantages and difficulties with this type of testing. Eg; When parts of the vehicle are intruding into the occupant area and striking the dummy it is difficult to assess the difference in performance of various restraints. Thus this test type is generally reserved for final concept proof, rather than development, research or approval testing.

## 2.2 DYNAMIC IMPACT SLED TESTING

This is the type of testing that is defined for approval testing of both adult and child restraints. It is also the most applicable test for development and research. The velocity, deceleration and angle of impact can be easily controlled, and thus repeatable test configurations are easily achieved.

There are limitations to the accuracy of crash representation with sled testing. Deceleration of the sled is generally uniaxial and thus the complex deceleration of a vehicle (6 degrees of freedom) can not be accurately represented. In addition, the deceleration pulse applied to the sled, in the single direction, is generally a very simplified representation of a crash pulse that would be observed in a real vehicle.

For most occupant restraint studies (including the work conducted for this thesis), this poor crash pulse representation is not

critical. The more important factor is the repeatability of the tests which allows a direct comparison of results to be made.

There are many types of sled test rigs and it is not appropriate to discuss them all in this document. The main differences between the tests conducted on the rigs are in the methods of achieving the required sled velocity and deceleration pulse. For example; the British Standard test rig decelerates the sled from the full 30 mph test speed, whereas HYGE rigs accelerate the sled from zero to minus 30 mph (backwards). Further detail on this test type will be in the form of a description of the test rig at the Road Safety Engineering Laboratory (RSEL), Middlesex University. This was the rig used for all of the experimental crash simulation, completed in this project.

#### 2.2.1 THE RSEL DYNAMIC IMPACT TEST RIG

The RSEL Dynamic Impact Test Rig at Middlesex University was constructed in 1980. The design of the rig was based on that used by the British Standard Institution (BSI), therefore the RSEL rig is capable of performing tests in accordance with appropriate British Standards. Many other international standards tests can also be performed, such as the European standard for child restraints ECE R44. It is convenient to describe the rig in its three major components;

- The Sled.
- The Instrumentation.
- The High Speed Film Analysis.

##### 2.2.1.1 THE RSEL SLED

The RSEL sled comprises a flat bed truck running on parallel rails, movement is restricted to one axis only. The truck is

pulled backwards by a cable and electric winch. This stretches the ten rubber chords which are attached to the sled, and after passing over a roller are anchored to the ground. When the truck is released, the rubber cords accelerate the sled to the required velocity. The sled is then decelerated in one of two ways;

- Aluminium crumple tubes.
- Polyurethane tapered tubes.

The aluminium crumple tubes are 1 m long cylinders (3" diameter, 0.075" wall thickness) which buckle axially when struck by the sled. The buckling force generated is approximately constant, yielding a roughly constant deceleration of the sled.

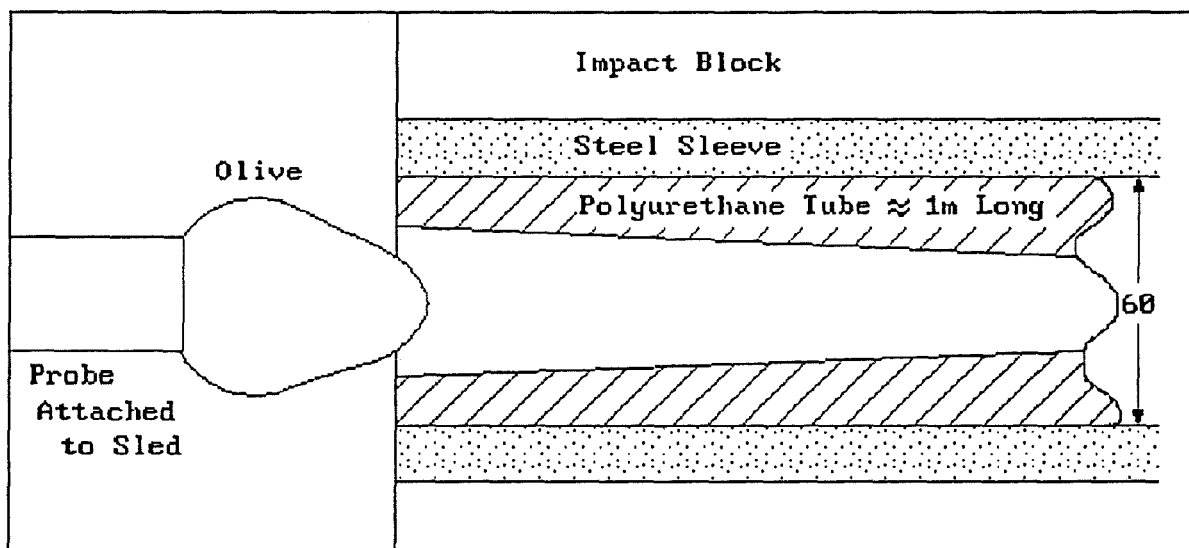
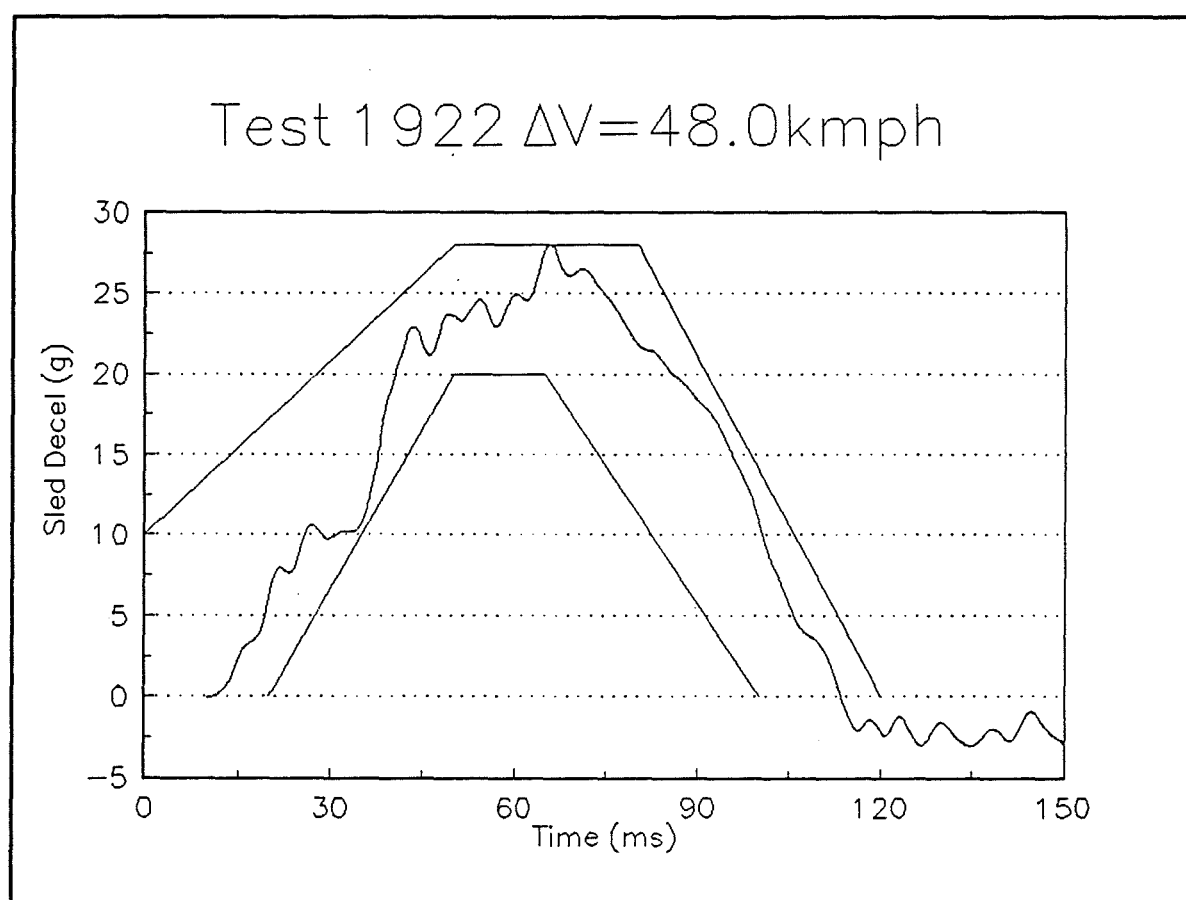


Figure 2.1 Polyurethane Tube for Sled Deceleration

The polyurethane tapered tubes are held within steel sleeves which are rigidly fixed to the impact block (see Figure 2.1). Probes attached to the front of the truck have an olive (tapered steel ball) on the end, which is of larger diameter than the tapered hole in the tube. The olive is guided into the tube as the sled approaches. The tube absorbs the sled energy by quasi-plastic deformation as the olive is forced down its length (the



tube will reform to its original shape in 24 hours). The polyurethane tubes are the defined method of sled deceleration in the European and British standards for seat belt and child restraint testing. They provide a repeatable method of sled deceleration which is roughly sinusoidal in shape. A typical deceleration pulse for a child restraint test is shown in Figure 2.2. Corrections, in the form of olive size changes, have to be made for changes in temperature and tube wear if consistent decelerations are to be achieved.



**Figure 2.2** Typical sled deceleration pulse using Polyurethane tapered tubes

The sled is a flat bed truck, to which various test seats and floor pans can be bolted. Test seats are available for adult seat belt testing (as defined in ECE Regulation 16) and for child restraints. Also available are flat plates which represent coach

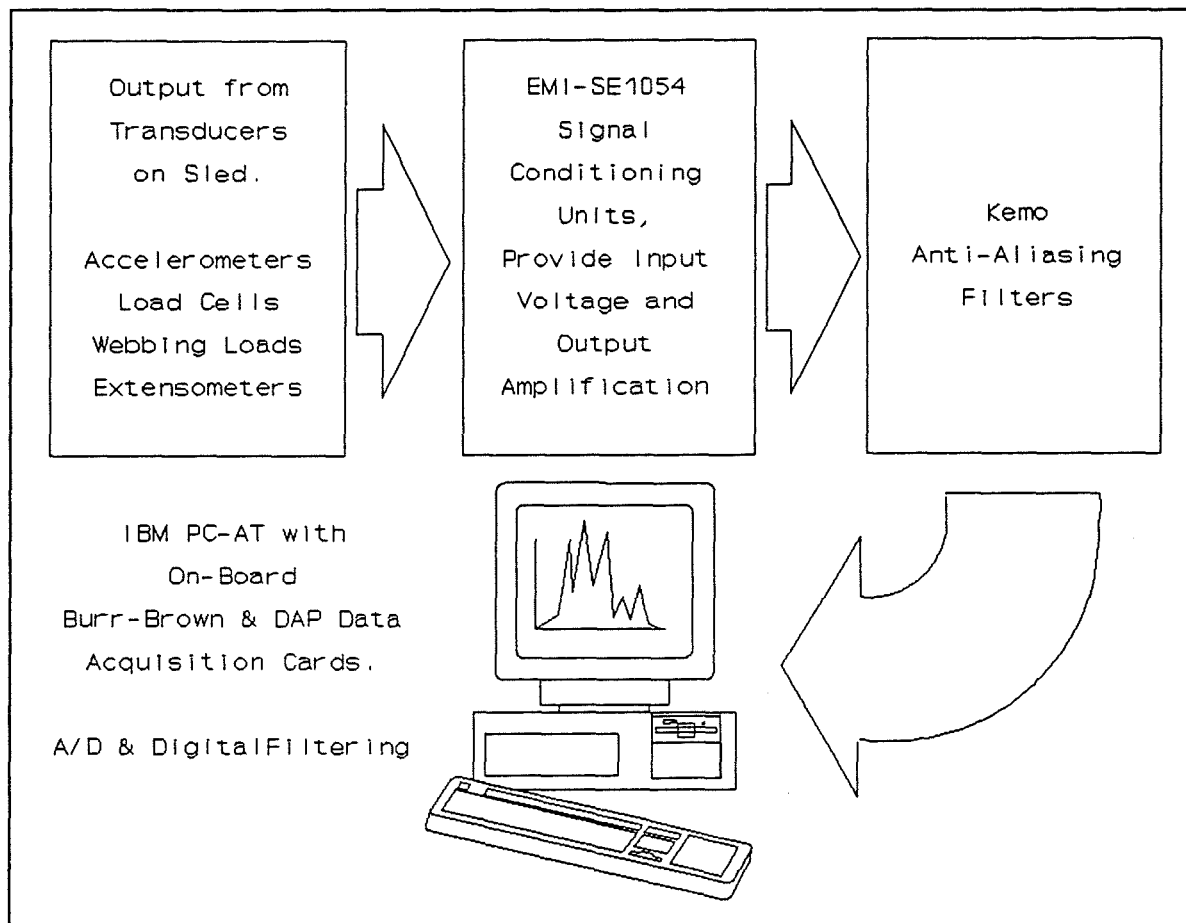
and minibus floor pans. In addition vehicle body shells can be bolted to the sled in order that a more realistic seating arrangement can be effected. The test seat that is used for child restraint testing is defined in the British (BS3254:Part2:1988) and European (ECE R44 1981) Standards. Both standards require the same seat design, except that the British standard defines a hinged seat back. The hinged seat back folds forward under impact to simulate a seat back catch failure.

#### **2.2.1.2 INSTRUMENTATION**

The instrumentation used at RSEL conforms to SAE recommended practice J 211a and is shown in Figure 2.3. Transducers, such as accelerometers and load cells, are supplied with an input voltage by the EMI-SE1054 signal conditioning units. These units also provide amplification of the analogue output signal. These two components are linked by an umbilical chord which trails behind the sled during the test. The signal is then passed from the signal conditioning units to Kemo Anti-Aliasing filters and then into the data acquisition system.

The data acquisition system comprises two data acquisition cards which are mounted in an IBM PC-AT personal computer. One is an 8 channel Burr-Brown card and the other a Microstar DAP data card which is capable of measuring 23 channels. The data acquisition rate is set at 10000 samples/sec. The data acquisition cards convert the analogue signal to digital form (A/D conversion) and save the data on the hard disk. A software package called ASYST is used to control the cards and analyze the data. Digital filtering and of the data is conducted by ASYST using a Butterworth filtering system and the data is also converted by multiplication with a calibration factor. The data is then saved

in its converted form and can then be graphed and analyzed.



**Figure 2.3** Block diagram of RSEL instrumentation

#### **2.2.1.3 HIGH SPEED FILM ANALYSIS**

Two main methods of visual recording are available at RSEL; High speed Cine film cameras and a High speed Video Analyzer. The high speed cine camera which is generally used is a Hadland Hyspeed S2, which is capable of recording at 10,000 frames per second. It is commonly used at a rate of 500 frames per second with 16mm colour negative cine film (Eastman 7292). The film must be developed before viewing which takes at least 24 hours. Analysis of the film is conducted using a PCD film analyzer with a Vanguard projector head. Scaled measurements can be taken using a calibrated graticule on each frame of the film.

High Speed Video Analysis is conducted using a Kodak Ektapro 1000

Video Analysis system. This system comprises; one CCD video camera linked to the main recording and processing unit. The system is controlled either from a menu-driven keypad or using a PC based software package called MOPRO. The digitized images from the camera are recorded in real-time on a specially designed video tape cassette, which is loaded in the main unit. A recording can be viewed immediately after the test. The video image is composed of a 240 x 192 pixel array with 256 grey scale levels (the image is black and white). Measurements of the recording can either be directly made in pixels using the keypad controller or scaled measurements can be made using the MOPRO software. Accuracy of the measurements is limited by the number of pixels which create the image and definition of two objects with similar grey scale. Typically the best accuracy of this system is  $\pm 4\text{mm}$  although this depends upon how close you zoom into the object you are measuring.

When comparing the two visual recording methods, clear advantages can be noted in both. The cine film yields high quality colour images which allow greater accuracy of measurement, due to the recording media and colour definition. However the cine film must be processed and thus can not be viewed during a test series, in the same manner as the high speed video. The digital nature of the video system and the PC control also allows for simpler transfer of measurement data to other PC software packages.

### **2.3 MATHEMATICAL CRASH VICTIM SIMULATION**

Mathematical Crash Victim Simulation (CVS) can be as simple as a single mass and spring model, or as complex as a finite element model consisting of many thousand elements. The very simple models can be exercised on paper, but these type of models do not

provide results of any real value. It is impossible to represent a multi-element structure such as a test dummy by a single mass and get any reasonable values for occupant injury. Thus a more complex multi-body or dynamic finite element model is required. To solve the more complex models a computer is generally used and software packages have been developed for the express purpose of Crash Victim Simulation (CVS). One such computer software package is MADYMO (MAThematical DYnamic MODEL). This package was purchased on an educational licence for use in this project. The following section will consist of a brief introduction of the concepts and construction of a MADYMO model.

Mathematical models have several advantages over experimental tests. These include:

- Faster simulations
- Lower cost
- High flexibility
- No experimental error
- Simple to conduct 'parametric' type studies

Mathematical simulations are generally faster to conduct as there is no set-up time between runs. The user merely alters a few numbers to create a new impact scenario.

The speed of simulation is one factor which contributes to the lower cost of CVS. In addition, there is lower manpower required and less cost required in consumables.

CVS is highly flexible in the impact scenarios which can be simulated as there are no physical limitations imposed as there are in experimental situations. Mathematical models are not subject to experimental errors, although is subject to modelling

simplifications and user error.

Parametric studies are simple to conduct with mathematical models as a feature can be changed independently of other parameters. This is often not the case with experimental tests.

All these features make mathematical crash victim simulation a highly useful tool to be utilised on this research project. However, as with any model, it is essential to be aware of the limitations of the technique. Inherent in models are assumptions and simplifications. The model must generally be a simplified representation of the actual product or scenario so that it is solvable and a practical size. These simplifications introduce modelling errors which must be considered when examining the results.

#### 2.3.1 MADYMO CRASH VICTIM SIMULATOR

MADYMO is a multi-element dynamic lumped mass model that was developed at the TNO Road Vehicles Research Institute (Delft, The Netherlands) for the simulation of occupants in car impacts. Since its conception, it has also been used for pedestrian impact, cyclists, wheelchair users, sports injury assessment, aircraft impact and many other varied applications. It has a flexible data input system that will allow the simulation of any large displacement body motion in either two or three dimensions. The three dimensional version of MADYMO was used in this project and thus the discussion that follows is based upon that version.

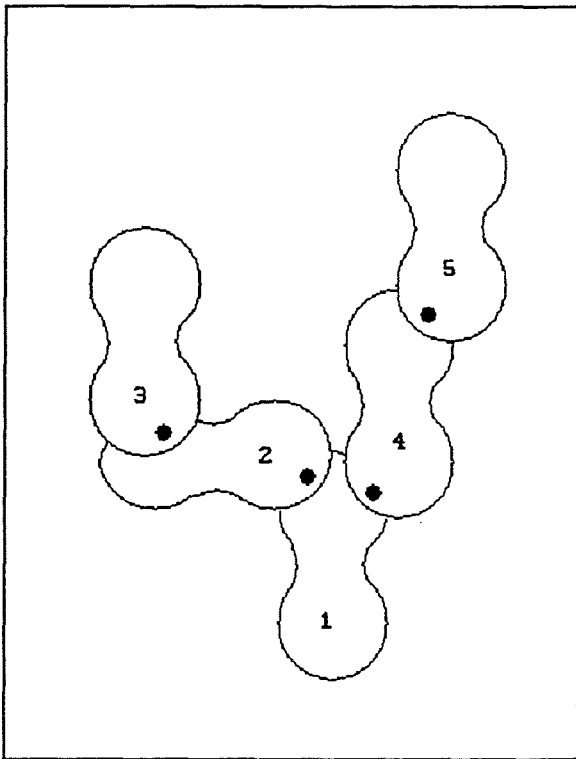


Figure 2.4 MADYMO 5 element tree structure

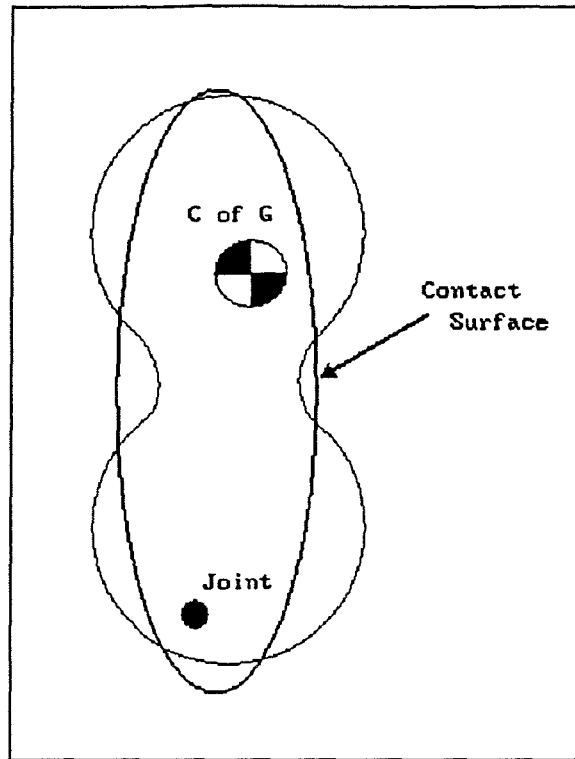


Figure 2.5 Single MADYMO element

The system to be simulated is represented by a tree structure of rigid elements that are connected by joints (see Figure 2.4). Each rigid element in a system (see Figure 2.5) is assigned a mass, centre of gravity position (relative to its joint) and moments of inertia (about the three axes). Each element has its own fixed local coordinate system which rotates with the element. It has an origin at the element's joint and all spatial locations are referenced to this coordinate system (see Figure 2.6).

All elements, except for the root element (Number 1 in Figure 2.4), have a joint which connects them with the lower numbered element. This joint can be one of two types, either a flexion-torsion joint or a cardan (ball & socket joint). Each joint requires a defined stiffness characteristic, such as shown in Figure 2.7, for each of the axes of rotation (three for the cardan joint). Loading and unloading curves are input in the form

of X-Y coordinates with the hysteresis curve defined purely as a slope.

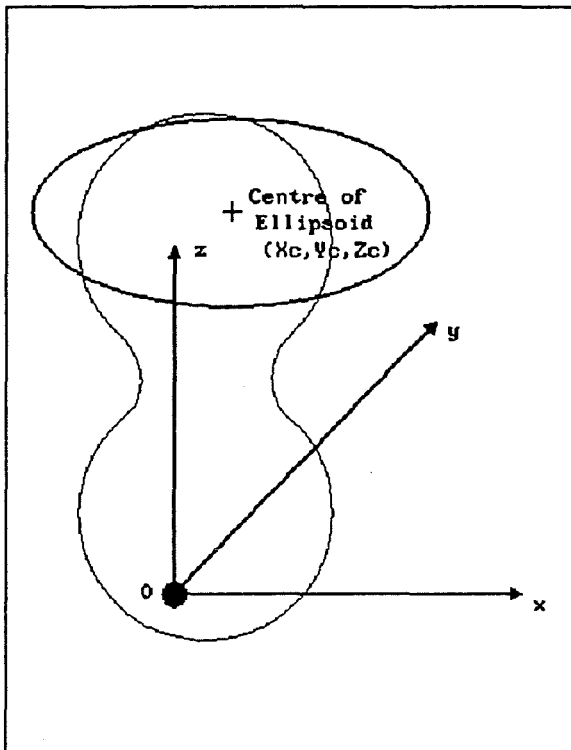


Figure 2.6 MADYMO element coordinate system

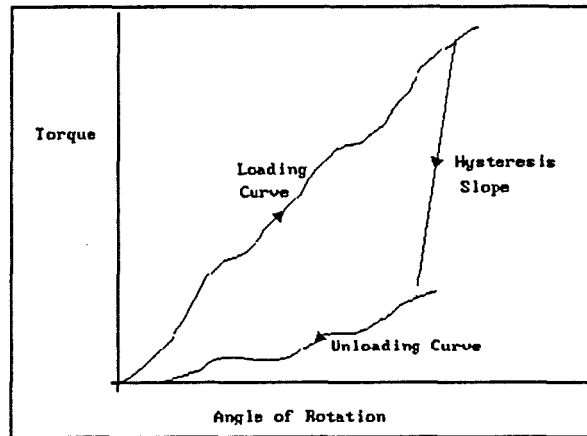


Figure 2.7 Example torque-rotation characteristic

The other major feature that may be defined for an element, is the contact surface. If no contact surface is specified then the element is shapeless and will not contact any other body. Contact surfaces that can be defined are either ellipsoids or planes. Many ellipsoids and planes can be assigned to a single element in order to create a complex shape. The ellipsoids can be of any order above one. That is, they can be made more rectangular than elliptical. The formula for an ellipsoid is as follows;

$$\left(\frac{X}{a}\right)^n + \left(\frac{Y}{b}\right)^n + \left(\frac{Z}{c}\right)^n = 1$$

Where:  $n$  is the order of the ellipsoid ( $n \geq 2$ )

$a, b$  &  $c$  are constants, the semi-axes of the ellipsoid

Many tree structure systems can be constructed, which allows for the simulation of multiple occupants, vehicle structures and restraint systems.



There are also two special systems which can be defined in MADYMO. They are the Inertial and the Null systems. The Inertial system is fixed in space and contact surfaces can be attached to it. No jointed elements can be defined for this system. The null system is similar in construction, but it is not fixed in space. A displacement - time characteristic can be defined for this system. Either of these systems can be used to define the vehicle or sled in which the occupant is seated. If the Null system is used, then the displacement - time characteristic of the vehicle is defined for the null system. If the Inertial system is defined as the vehicle, then the deceleration of the vehicle is applied, in the opposite direction, to the occupant see Figure 2.8.

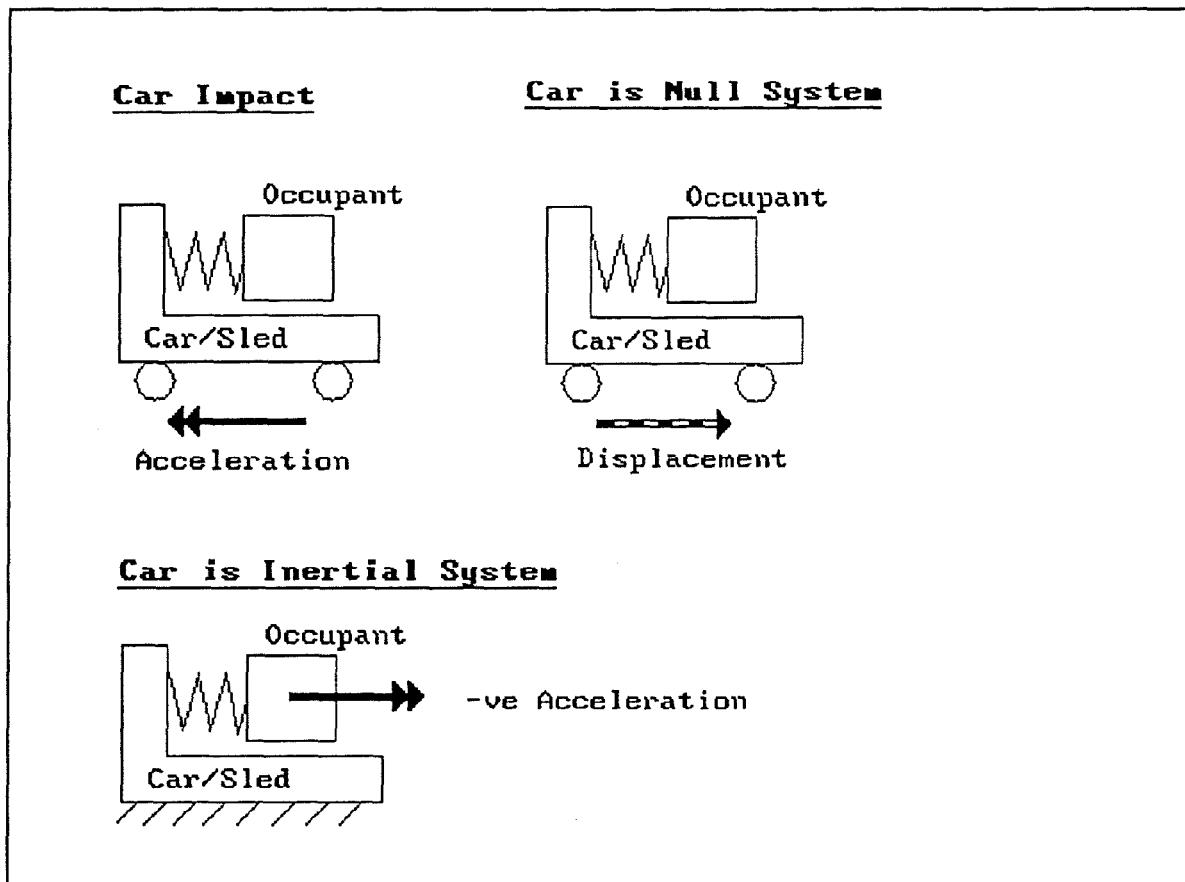
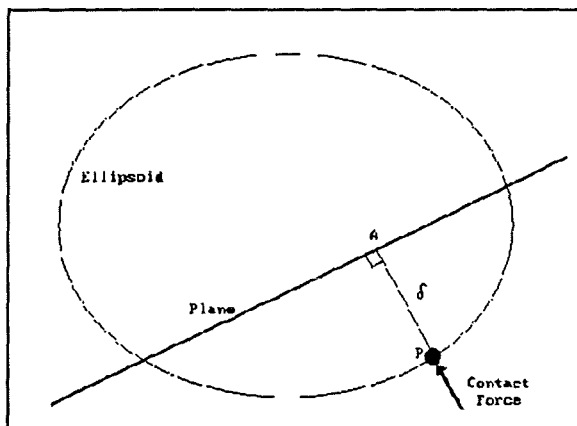


Figure 2.8 Definitions of the Car in MADYMO

The various systems in a simulation interact via belt systems, point restraints and contact interactions. Seat belts are

simulated using a belt system subroutine, which can allow for slip, spool out from a reel and deformation of anchorages. However, the belts are defined by attachments to a specific point on a system element. As such the belts cannot slip over or off an element, which makes situations such as submarining difficult to model.



**Figure 2.9** MADYMO penetration definition

Contact interactions can be defined between two contact surfaces, either ellipsoid - ellipsoid or plane - ellipsoid. If no contact interaction is specified the two bodies will pass through one another. The

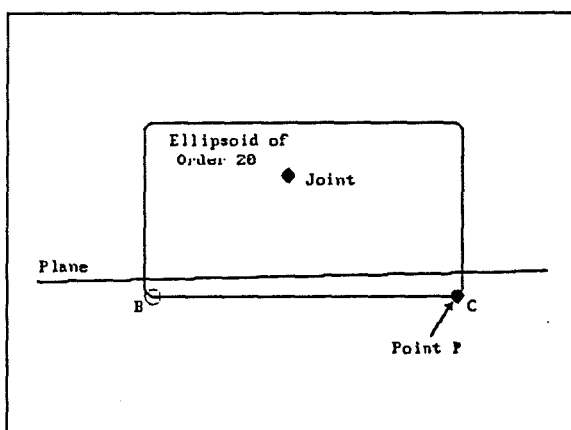
contact force is defined by a

penetration - force characteristic, which is similar in form to the joint stiffness specification shown in Figure 2.7.

The contact interactions between two surfaces are defined as shown in Figure 2.9. This diagram shows an ellipsoid - plane contact interaction, but the definition of contact force is the same for an ellipsoid - ellipsoid contact.

The point of deepest penetration

is calculated from the positions of the surfaces and their dimensions. The contact force is then calculated for the measured penetration  $\delta$ . The force is interpolated from the penetration - force function that is defined by the user and applied to the ellipsoid at point P, in a direction which is coincident with the



**Figure 2.10** Penetration of a rectangular ellipsoid

penetration line A-P. This method of contact definition is not an accurate representation of some contact cases. Firstly there is no calculation of the contact area, and thus fluctuations in force due to changes in area are not accounted for. Secondly large changes in the point of application can occur, if the ellipsoid is of a high order (more rectangular in shape). This problem is illustrated in Figure 2.10. The point of deepest penetration P, can be moved from ellipsoid corner C to corner B, with only a small rotation of the ellipsoid's element. Thus the contact force can induce either a clockwise and an anti-clockwise moment about the element joint. This can make large differences in a kinematics of a simulation and in some cases induce oscillation.

The output from MADYMO is in numerical form and requires post-processing if a graphical form is required. For a visual representation of the occupant kinematics, a post-processor called MGLOT is supplied with the main MADYMO software. This is a relatively simple post-processor which constructs line drawings of the objects that are simulated. All ellipsoids are represented as order 2, even if they are of higher orders. For the time history plots of for example acceleration, other software packages must be used. All the plots that are shown in this report are created using either ASYST<sup>1</sup> or AXUM. In either case a separate ASYST program was also used to organise the data from the MADYMO files into a form that is more easily used. Both of the graphing packages are PC based and thus the data must first be down loaded from the Mainframe computer to the PC.

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<sup>1</sup> ASYST and AXUM are commercially available software packages for the analysis of numerical data.

All of the output data from MADYMO is user defined. The user must specify what output is required and from what location in the simulation. For example; Linear Acceleration, at a location in the head of the dummy, relative to ground.

3 THE BIOMECHANICS AND OCCURRENCE  
OF INJURIES TO CHILDREN  
IN CHILD RESTRAINTS

### 3 THE BIOMECHANICS AND OCCURRENCE OF INJURIES TO CHILDREN IN CHILD RESTRAINTS

The child is not just a small adult. There are particular biomechanical problems in restraining an underdeveloped human body which require more complex restraints than adults. This chapter will first quantify the injuries that are occurring to restrained (and unrestrained) children. Following that there is a summary of the particular features of child physiology, anatomy and anthropometry, that are important when considering child restraint design and child injury. Finally, a summary of the known injury tolerance data is included.

#### 3.1 INJURIES OCCURRING TO CHILD CAR OCCUPANTS

Retrospective analysis of field accidents is the most appropriate method of assessing the effectiveness of a production restraint. Injury potential can be reduced by using laboratory tests, but until the restraint has been observed in a real crash environment the actual injury reduction cannot be calculated.

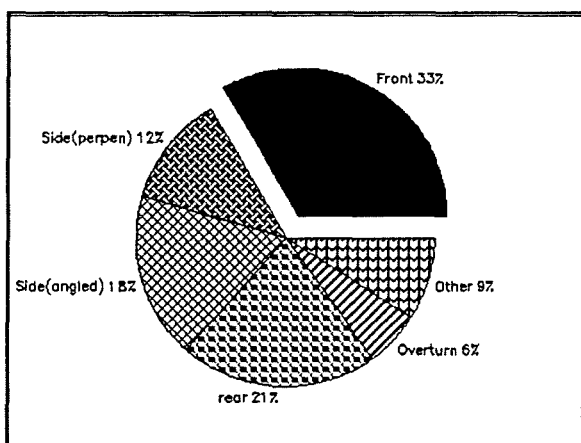
The investigation of actual injuries also provides valuable feedback into the restraint design procedure. This feedback can be in the form of modifications to existing designs or suggestions of additional protection features. The introduction of an injury reduction method will affect the injury patterns that are observed in accidents. Thus older accident studies will not be discussed in this document.

Until recently injury patterns were studied in only local or national data sets. This has reflected the local nature of child restraint and car design. With the greater harmonisation of such products it is expected that more international studies will be

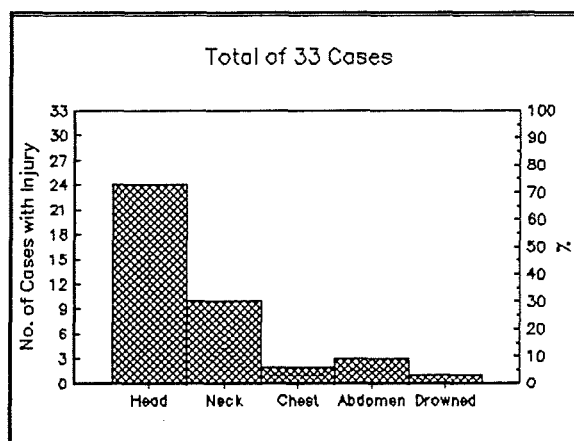
possible. This is recommended as an individual country will have only a relatively small quantity of injuries to child car occupants, a much greater sample is required for any statistically significant study.

Many of the injury pattern studies that are conducted can not be any more than anecdotal. For example the only national child injury study that is conducted in the UK is on restrained child fatalities (Gloyns and Rattenbury 1991). And in the 10 years between March 1989 and January 1991 only 116 cases occurred. It is unlikely that in this relatively small sample that there will be several similar cases (or even two similar cases), and thus a statistically valid proof of any theory based upon this data is difficult to achieve. What is needed is a massive in-depth study of all injuries to children involved in car impacts.

### 3.1.1 INJURIES OCCURRING IN THE UNITED KINGDOM



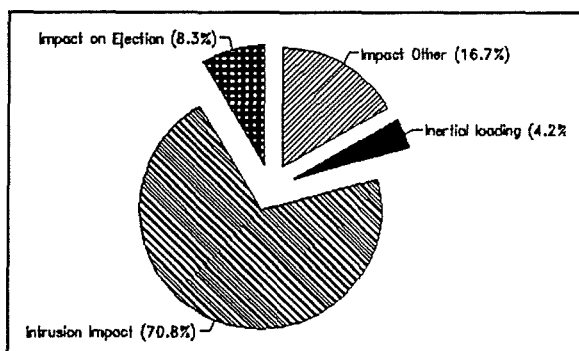
**Figure 3.1** Impact type in fatal injuries to restrained UK children. Data set from Lowne et al (1987)



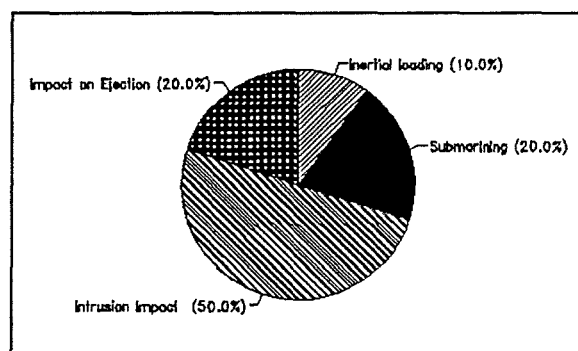
**Figure 3.2** The fatal injuries to restrained children in UK data set from Lowne et al (1987)

Most of the fatalities which occurred to restrained children in the UK between 1972 and 1986 were reported by Lowne, Gloyns and Roy (1987). This sample (33 in total) did not include any frame

type child seats held with an adult belt, as they were only beginning to become popular during this period. However, the data is presented here to show the general injury mechanisms to restrained children involved in automotive accidents. Figure 3.1 shows the proportions of accident types. Frontals are shown to be the largest single group (33.3%), but side impacts are shown to be of a similar proportion (30.3% if side angled and perpendicular are taken as one group). Figure 3.2 shows the location of the injuries that occurred to the 33 children in this sample. The total percentages add up to more than 100%, as many children had more than one injury. It can be seen that head injuries are the most common at 72%. Neck injuries then follow as the second most common. The causes of these two injury types are shown in Figure 3.3 and Figure 3.4 respectively.



**Figure 3.3** Causes of head injuries to the data sample in Lowne et al (1987)



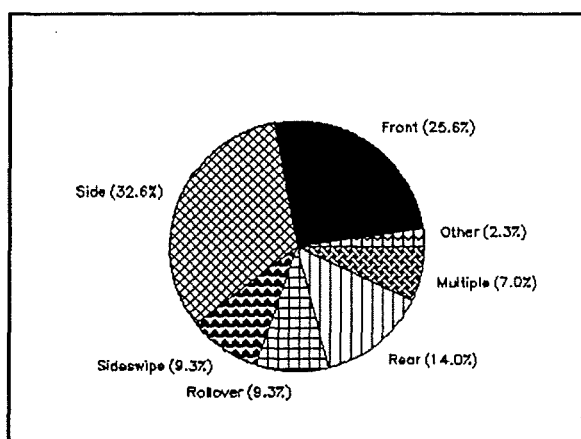
**Figure 3.4** Causes of Neck injuries to children in data set of Lowne et al (1987)

When considering the distributions it should be remembered that the sample sizes are small (24 head injury, 10 neck injuries). However, the data shows that impact on an intruding part of the vehicle predominates as the major injury cause for both the head and neck. Impact on ejection from the seat is also a high injury cause. The high incidence of ejection is not necessarily an indicator of poor child restraints. The reason for ejection varies; misuse of restraint, additional loading from another

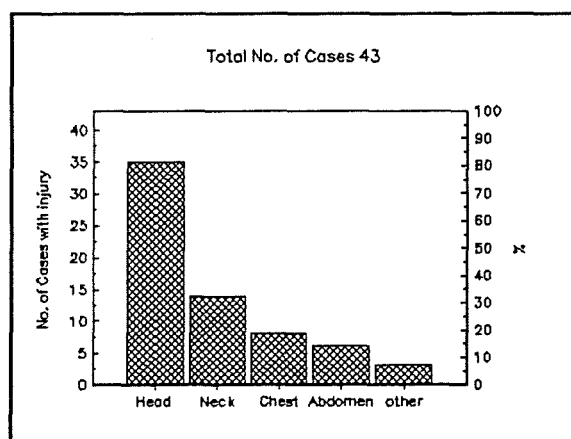


occupant and the use of unapproved child restraints are all causes. An apparently minor injury mechanism is damage from purely inertial loading.

The data published in Lowne et al (ibid) was from an ongoing fatal accident survey that is sponsored by the Transport Research Laboratory (TRL) in the UK. More recent results for this work are published in several documents which are included in the references as Gloyns and Rattenbury (1991). This data sample includes all restrained child fatalities for the period 1979 to 1989 (116 fatalities). The cases which involved children in child seats of the 9 month to 4 year age range are summarised here (43 cases).

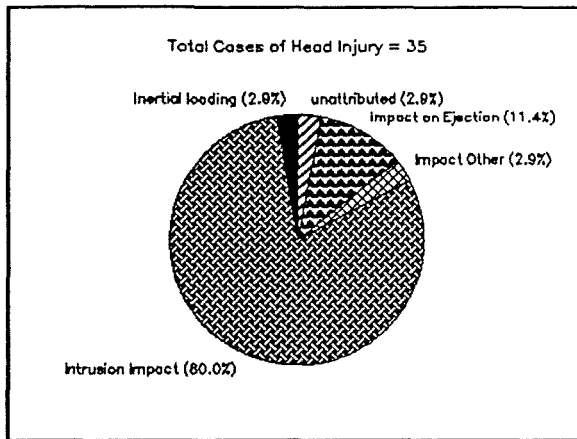


**Figure 3.5** Impact type of child fatal crashes in data set from Gloyns & Rattenbury (1991)



**Figure 3.6** Area of injury to children in Gloyns & Rattenbury (1991)

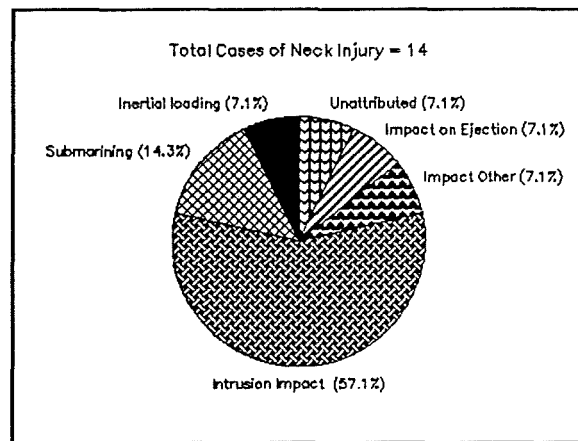
Side impact is a greater proportion of the total in this sample (Figure 3.5). If Side and sideswipe are added together they represent 41.9% of the impacts. However, the pattern of injuries to the children (Figure 3.6) and the causes (Figure 3.7 and Figure 3.8) are similar to that reported in Lowne et al (1987). It is not surprising that within the small samples of data that are shown here, there will be variations in the data.



**Figure 3.7** Causes of head injury in the Gloyns & Rattenbury (1991) data set.

The biomechanical factors which contribute to the predominance of head and neck injury are discussed in section 3.2.1.1. Any injury to these parts of a persons anatomy is likely to be serious. The head contains the brain and the neck contains the

cervical cord, the link between the brain and the rest of the body. Therefore it is not surprising that in any fatal accident sample, head and neck injuries are likely to predominate. In both samples the major cause of head and neck injury is an impact with an



**Figure 3.8** Causes of neck injury in Gloyns and Rattenbury (1991)

object intruding into the passenger compartment. That object may be part of the vehicle itself, a striking vehicle or another object. It is difficult to protect against this type of injury by design in a child restraint. Improvements in occupant protection could only be achieved by strengthening of the vehicle body, thus reducing the intrusion.

The "Impact other" section of the graph and some of the ejection injuries are mainly caused by misuse of the child restraint or loading of the child and restraint from another source, eg. another occupant. Again it is difficult to protect against such injuries, except through education and design against misuse.

### 3.1.2 INJURIES OCCURRING IN OTHER COUNTRIES

The West German child injury experience was presented by Langweider and Hummel (1987). This paper describes the accident and injury distribution to both unrestrained and restrained child occupants in vehicle accidents between 1970 and 1986. The data was compiled using a questionnaire and thus may be subject to bias and inaccuracies. The age range of the children in this data is 0 to 12 years. The results of this survey exhibit very similar trends to that seen in the UK. 51.3% of accidents were classified as frontal, 23.6% Side, 22.8% rear and 2.3% rollover. Amongst restrained children head injuries were dominant (60.4%), followed by neck injuries (15.3%) and abdominal injuries at (13.9%).

There were a total of 865 restrained child cases in the Langweider and Hummel data. Only 13 of these cases were in the serious injury, AIS  $\geq 2$ , injury category. This may be due to the understandable reluctance of parents of seriously injured or killed children to discuss the incident. All of the serious injuries bar 1, were concentrated on children below the age of 4. All of the cases above AIS of 3 were concentrated further into the under 2 years old age group. The reason for this is not clear, perhaps it is due to the anatomical differences in the young child. It should be noted that the method of child restraint in Germany differs from that of the UK. Infants are restrained in the same manner, but the toddler age group is commonly restrained in a shield type child restraint. On a more general note, the restrained child was found to be injured far less frequently than the unrestrained (17.3% compared with 51.4%).

The accident situation in France was summarised by Valleeé et al

(1991). This document describes similar injury patterns to those in the UK and in the Germany. The most notable feature of this work is that no statistical difference was found between the fatality rate for unrestrained and restrained children. This was due to a variety of factors which are discussed in section 4.2.2.2.

Carlsson et al (1983) presented the findings of Volvo's ongoing

**Table 3.i** Child injury frequency (AIS 1-6) in Sweden taken from Carlsson et al (1983)

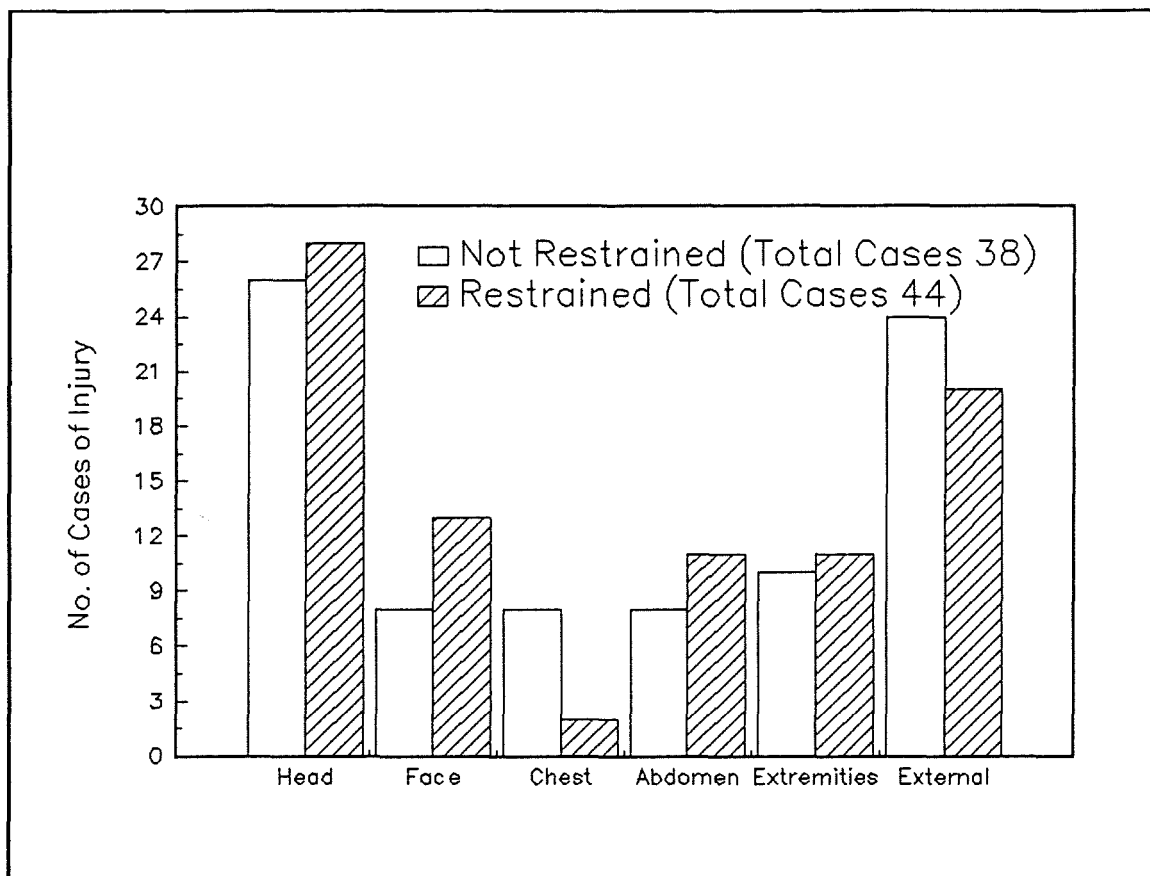
Body Area	Front		Rear		Child Seat	Carry-cot etc	Others
	Belt-ed	un-belted	Belt-ed	un-belted			
Head	12.8	46.4	8.5	20.3	8.5	15.9	23.1
Neck	8.3	-	-	1.9	-	-	0.6
Spine	1.9	-	-	1.4	-	-	1.8
Chest	3.8	-	1.7	1.9	-	-	1.2
Stomach	0.6	-	-	0.8	-	-	0.6
Hips	0.6	3.6	-	0.8	1.4	-	0.9
Arms	9.0	10.7	5.1	6.8	1.4	2.3	5.8
Legs	5.1	21.4	21.4	6.9	-	2.3	5.0

accident research in Sweden. Table 3.i is copied from this work and shows the injury frequency, for children under 14, related to body area and restraint method. It can be seen that an unbelted child is more likely to be injured than a restrained one. This is true for both front or rear seats of the vehicle. Child seats are shown to have the lowest overall injury levels. The child seat in Sweden is a rearward facing device up to the age of 4 or 5 years. This has been shown in other work (Turbell 1989) to be more

effective than a forward facing restraint. When the injury frequency is considered in relation to body area, again head injury is shown to be dominant. No incidence of neck injury is shown to occur in the rearward facing restraints. Turbell (1989) stated that only three fatalities have occurred in rearward facing child seats. Of those three cases, one fatality was due to a fire and the other two were due to gross intrusion into the passenger area. It was also stated that Sweden has the lowest fatality rate of the under 6 year age group of the 15 western countries that were shown.

An article was published, by Hoffman et al (1987), which studied injuries to children in motor vehicle accidents in Canada. This document was based upon injured children that were admitted to a particular childrens' hospital in Toronto, and thus is not necessarily an unbiased sample. No non injury cases are included in the sample, thus no conclusions of restraint usage or effectiveness could be drawn. Injuries to the both restrained and unrestrained occupants were presented, and are shown in Figure 3.9. It can be clearly seen that the injury patterns to the restrained and unrestrained occupants are very similar. This is not surprising when you consider that the injury mechanisms are likely to be similar in both cases.

Neck injuries are not shown in Figure 3.9, but two fatal neck injuries were presented in this paper. Both were restrained children, one aged 7 years and one 3 year old. Both cases were C1-2 injury. No details of child seat type, misuse or vehicle impact are presented and thus further examination of these cases is not possible.



**Figure 3.9** Injuries to restrained and unrestrained occupants in the Hoffman et al sample.

### 3.1.3 INTERNATIONAL INJURY STUDIES

An international injury study is a necessary addition to the current research programmes. As has already been mentioned, the sample size of child fatalities and injuries in any one country is small. Introducing an international treatment of the problem will greatly increase the sample size.

Tarriere et al (1991) reported the initial conclusions of an international task force consisting of experts from 7 countries. The countries are; the UK, France, USA, Sweden, Germany, Australia, and Canada. This study is in its initial stages and no general injury data has yet been issued. This, the first document to be published deals with the initial observations made from the data. Neck fracture was a concern of the task force, particularly in respect of forward facing child seats. However, only eleven

cases of fracture were found in children properly restrained in forward facing child seats. This was out of a sample of several thousand cases. Neck injury was still considered to be of concern, as it appears that it can be prevented with existing restraint methods. No cases were found where the child seating system included a top tether. The top tether reduces excursion and thus the occurrence of head impact. Also no cases were found in rearward facing seats.

One of the other conclusions of the international task force was concerned with differences between certification testing and the real car environment. It was observed that child restraints had diminished effectiveness in actual vehicle crash tests when compared with certification tests. Suggested areas of study were cushion stiffness, anchorage geometry and belt tension.

The international concern over neck injury was the inspiration for two papers on cervical injury by Huelke et al (1992 and 1992a). One of these papers deals with adult injury and the other child injury cases. Both papers deal with restrained occupant, non-head impact injuries in the UK, USA and other countries. Eleven cases of restrained child cervical injury were presented in Huelke et al (1992a), most of which were injuries in the upper cervical spine (C1/C2). It was stated that these injuries were very rare. However, no reason for this was given. Could it be that the reason is that, in the majority of serious accidents impact of the head occurs. If this is the case then we may expect to observe an increase in frequency of neck injury as car safety is improved and intrusion is reduced. In recent years safety has become a major selling point and safety cages and side impact bars have been introduced. If these measures have the

desired effect, i.e. to reduce intrusion, then injury due to head impact may reduce and neck injury become more frequent.

### 3.2 CHILD PHYSIOLOGY, ANATOMY, ANTHROPOMETRY AND INJURY MECHANISMS

This section will deal with the physiological and anatomical problems of the restraint of children. Also included is a brief overview of the changing anthropometry of the developing child.

#### 3.2.1 CHILD PHYSIOLOGY AND ANATOMY

The physiology and anatomy of the child differs in many respects to that of the adult and has a distinct effect on the available methods of child restraint. For convenience, the presentation of these affects will be divided into the various body regions. The head and neck will be discussed first of all. This area includes the most important of the anatomical differences between child and adult.

##### 3.2.1.1 THE HEAD AND NECK

Injury to the head of the child or adult can occur in two ways. Firstly by direct head impact and secondly by inertial loading of the brain matter. This project does not address injuries that are caused by head impact, although these are the most common injuries (see Section 3.1.1). This type of injury is mainly caused by intrusion, and little can be achieved by design of child restraints, except to minimise head excursion, to reduce head impact. Thus the subject of impact injury will only briefly be covered here in the form of an analysis of child anatomy. The mechanics of the actual injury will not be discussed.

The proportional size of the head of the child is much greater



than that of the adult (see Figure 3.14). At 18 months the child's brain attains 70 % of the adult mass and at three years this figure rises to 80%. This higher relative size of head to total body size means that if an impact occurs to the child body, on a purely statistical basis, head impact is more likely. It has been shown that this is the case (Moore et al (1959)).

The ratio of face to cranium area is also very different in the child. In the newborn this ratio is 1:8 whereas in the adult this ratio is 1:2.5. This is due to the relatively large brain size and in particular to the massive frontal lobe of the brain, which means that the forehead is quite bulged. The greater proportion of cranium area means that any impact to the head is more likely to occur directly to the cranium and subsequently the brain area.

The cranium itself is more flexible and weaker in the child than in the adult. The skull is composed of several bones. The Frontal, Parietal, Occipital, Temporal and Sphenoid bones. In the child these bones are not rigidly linked but joined by a thin fibrous sheath (Fontanelles). These flexible junctions are quite wide and therefore comprise soft areas in child's skull. In addition the bones themselves are quite thin and therefore flexible. The Fontanelles close at various times in the child's development. The Mastoid fontanelle, between the occipital and parietal bones, closes at about 6 to 8 weeks after birth, whereas the frontal fontanelle closes at around 17 months (the term 'close' means bone growth over the area). The main question which remains to be answered is "Could the flexibility of this skull in the child mean that, direct impact injury to the brain could occur without skull fracture or bruising ?"

Gennarelli (1992) suggests that injuries which are typical in cases of direct head impact are;

Skull deformation injuries

Local: Skull Fracture (Linear depressed)  
Extradural Hematoma  
Coup Contusions

Remote: Vault and Basilar Fractures

Shock Wave Injuries

Contrecoup Contusion  
Intracerebral Hematoma

It is known that injury can occur in the brain by a purely inertial loading. One of the first people to consider the inertial loading of brain tissue was Holbourn (1943). Holbourn discussed the mechanics of head injury and the importance of rotational acceleration in inertial injury. The brain is not attached to the skull in which it is contained. Restraint on movement of the brain within the skull is from several sources. Firstly, the close fitting of the skull around the brain, which will restrain the brain in linear acceleration. Secondly, restraint of movement will come from the cervical chord which passes through the bottom of the skull. In addition friction between the brain, dura and skull and damping from the fluid surrounding the brain will resist movement. This lack of direct attachment between brain and skull means that when the head is put into motion, the brain movement lags behind the skull and strain can be placed upon the brain tissue and vessels. This strain is the cause of the non-impact head injuries. The most recent knowledge on this subject is summarised by Gennarelli (1992). This paper does not include information specific to child injury, but the mechanisms of such injury are likely to be similar. Typical injuries induced by inertial loading are as follows;

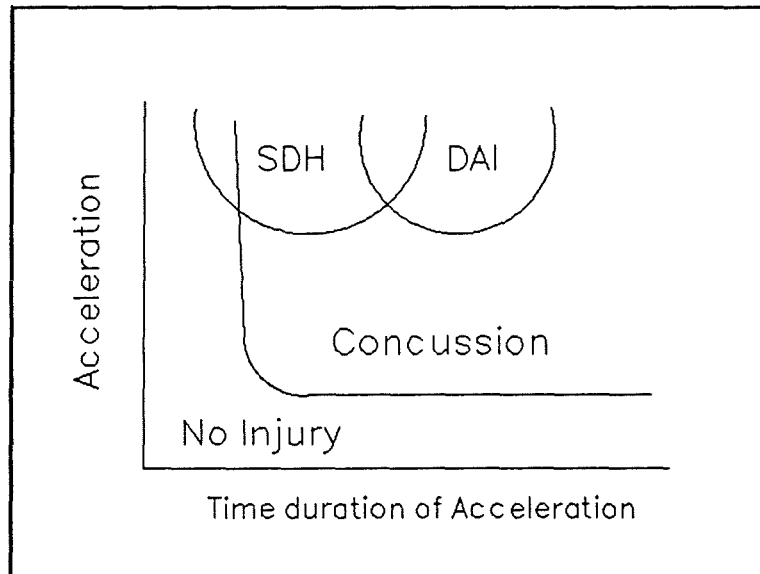
## Surface Strains

Subdural Hematoma (SDH)  
Contrecoup Contusion  
Intermediate Coup Contusion

## Deep Strains

Concussion Syndromes  
Diffuse Axonal Injury (DAI)

The type of injury received from an acceleration loading is dependent upon several factors; the direction of acceleration, the magnitude of acceleration, rate of onset of acceleration, velocity change and time duration of the



**Figure 3.10** Relationship between Brain injury type, acceleration magnitude and acceleration duration as conceived by Gennarelli (1992)

pulse. For example in an oral presentation of the paper by Gennarelli (ibid), the relationship between acceleration magnitude, duration and injuries received was plotted as shown in Figure 3.10. A similar plot which relates angular acceleration and velocity to injury is included as Figure 3.19. It should be noted that both of these plots are based upon adult injury data.

Holbourn (ibid) showed that linear accelerations produced only small strains in the brain surrogate, and that rotational accelerations are the likely cause of the vast majority of inertial brain injury. The rotational acceleration has been shown by Holbourn (ibid) and others to cause much higher strains than can occur with linear acceleration. It must be noted however

that it is virtually impossible to have rotational acceleration without some linear component in real life. A pure rotational acceleration would mean a rotation of the head about its' centre of gravity, but in real life rotation of the head is about some point on the cervical column. Thus linear and rotational acceleration are bound together in one movement (generally termed angular acceleration). Linear acceleration can occur briefly as a singular movement when, for example, the head strikes a hard object the resulting acceleration is initially in a uniaxial linear mode.

Angular acceleration can cause virtually every known type of head injury, with the exception of skull fracture and epidural hematoma. These injuries are all strain induced but vary in the type and application rate of that strain. Subdural hematoma (SDH) that is caused by inertial forces, comprises a disruption of the surface vessels of the brain. This is caused by a high strain rate, typical in short duration high peak accelerations. Diffuse Axonal Injury (DAI) is produced by longer acceleration loading with a lower rate of application than that which causes SDH. The exact mechanisms of such injury are not completely understood and little knowledge is available on the differences between adult and child injury.

The neck of the child has always been considered at particular risk from injury in car impacts. The child neck is an underdeveloped version of the adult neck. Visibly the neck is narrower in relation to head size than the adult neck. Together with the knowledge of a relatively larger head mass, it follows that the smaller neck will be subjected to relatively larger loads. Therefore a greater incidence of neck injuries could be

expected in children. The articulation of the neck is described by four terms as shown in Figure 3.11. Injury to the neck can come from any one of many 'overload' situations. Firstly from a compression of the spinal column, often caused by a impact on the top of the head. This can cause one of the cervical vertebrae to explode

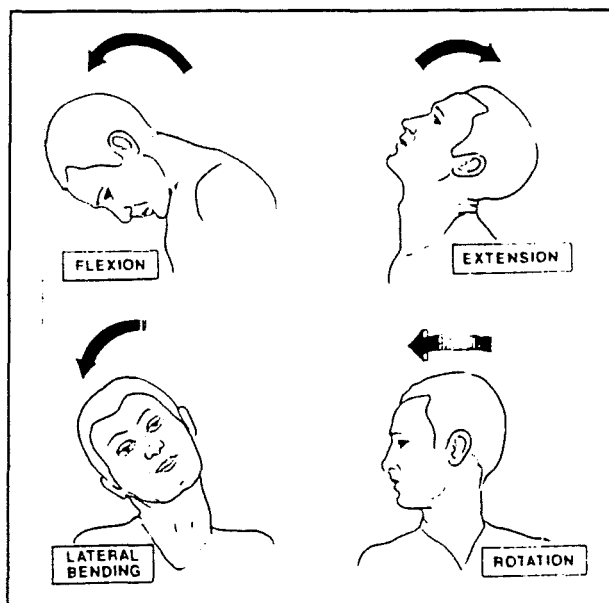


Figure 3.11 Descriptive terms of Head-Neck motion (taken from Huelke & Nusholtz (1986))

in a complex fracture. A tensile injury can also cause injury. Huelke et al (1992) quoted another source which stated that "In autopsy specimens the elastic infantile vertebral bodies and ligaments allow for column elongation of up to two inches, but the spinal chord ruptures if stretched more than 1/4 inch". Dislocation of the spinal chord can occur from a blow to the head in the horizontal plane. This would accelerate the head but because of inertia the torso would remain relatively still. This could lead to sliding of one vertebral element relative to another and cause dislocation, fracture or damage to the spinal chord. The final two major causes of neck injury in car impacts are hyperflexion and hyperextension. ie, over-bending of the neck. This could cause damage to ligaments and muscles or in extreme cases fracture and dislocation. The term "whiplash" is often used to describe different injuries. In this thesis, whiplash will describe a hyperextension injury (gross rotation of the head towards the rear of the body).

The cervical column of a child differs considerably from the

adult. The human cervical column is composed of seven cervical vertebrae, which are numbered from C1 at the head end to C7 at the torso. C1 and C2 differ in construction from the rest of the cervical column. C1 is the vertebrae which links to the head and is often referred to as the "atlas". C2, often called the "axis", is specially developed to link with C1 and includes the 'dens' an upright boney structure which fits through a hole in C1. The interaction of C1 and C2 is principally involved in the rotation of the head in the "no" gesture. At birth the cervical vertebrae are not bone but cartilaginous. Replacement of this structure with bone occurs slowly. The vertebrae joints also have a much greater mobility of horizontal movement (subluxation). This is due to two factors: (1) the ligaments are lax and therefore allow relative movement between vertebrae; (2) The facet joints in vertebrae C1-C3 are nearly horizontal and do not gain the adult angled orientation until the age of 8 years. This means that the vertebrae themselves provide little restraint when subjected to a horizontal load. The cervical musculature of the infant is also not developed in the infant and therefore cannot provide damping to any violent movement of the head. The last feature of the child neck which differs from the adult is the fulcrum of cervical movement (or bending). In the adult the fulcrum is at the C5-C6 level, whereas in the child it is much higher in the C2-C3 area.

In summation the child head is larger and has a higher relative mass than the adult head. This larger head is supported by a smaller and weaker neck which has an underdeveloped bone structure. The child cervical column is more susceptible to relative lateral displacement from forces imposed upon it. The head, because of its size, is statistically more likely to be

struck and imposes a relatively higher load on the neck than in the adult.

#### 3.2.1.2 THE TORSO

There are important differences between the child and adult torso that must be considered in child restraint design and injury assessment. The main problem with child torso physiology is the general flexibility of the torso. The thoracic wall of the child is thinner and the ribs much more elastic. This means that for a given load the deflection of the infant or small child torso is much greater than in the adult. The internal organs are therefore more exposed, and injury to the organs can occur with no external damage. The thoracic organs (predominantly heart and lungs) are the second most important organs in the human body, next to the brain. And any injury to these organs is likely to be considered serious or life threatening. The general low stiffness of the child chest is the reason for the full harness required in most framed child seats. The two wide shoulder straps, which are required in most child restraint design standards, spread the load over a greater area of the chest and therefore reduce possible belt loading injuries.

The infant child must have the torso loading spread over an even greater area than that which can be achieved with a harness. This is achieved by utilising a rearward facing child restraint, which spreads the load over the whole torso in a frontal impact. In addition this restraint type supports the head in impact and prevents major hyperflexion neck injuries.

### 3.2.1.3 THE PELVIS

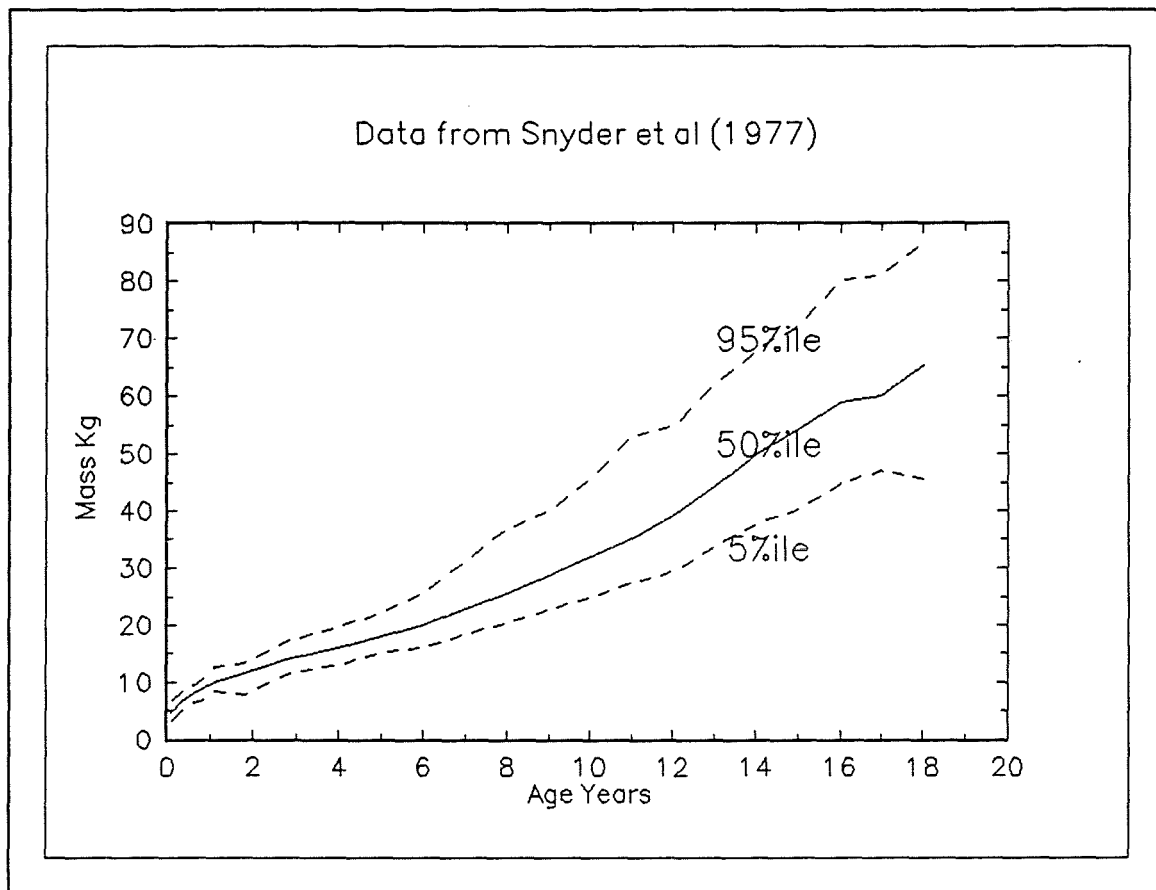
The underdeveloped pelvis of the child causes major problems in child restraint. The adult pelvis has fully developed iliac spines which are used as anchor points for the seat belt. The seat belt is designed to fit below these spines and be "locked" into position and therefore prevent submarining (submarining is the tendency for the pelvis to pass under the belt during an impact). These spines are not present in the child pelvis until the age of about ten years and the developing spines are cartilaginous. Instead the child pelvis has a smooth gentle curve of small area to which it is rather difficult to anchor any lap belt. A typical kinematic response of a child in a lap belt is for the pelvis to rotate backwards and pass under the belt (submarine). This allows the belt to rise into the soft and vulnerable abdominal area. To stop this rise of the lap portion of a child restraint harness, a crotch strap is included to hold the lap section down and away from this area.

### 3.2.2 CHILD ANTHROPOMETRY

The growth of children is not a regular linear event, but varies in generally predictable stages. Most body dimensions have periods of rapid growth which are separated by periods of relatively slow development. This can be observed in a graph of mass with age as shown in Figure 3.12. The most rapid period of post-natal child growth occurs just after birth. Between birth and 1 year the child's mass generally doubles. This rapid growth period then reduces in rate up to the age of around 11 years. At this point there is another period of more rapid growth, puberty. Of course for the purposes of this document we shall mainly be concentrating on the child of age 9 months to 4 years. Although this is not the period of most rapid growth, a child can almost



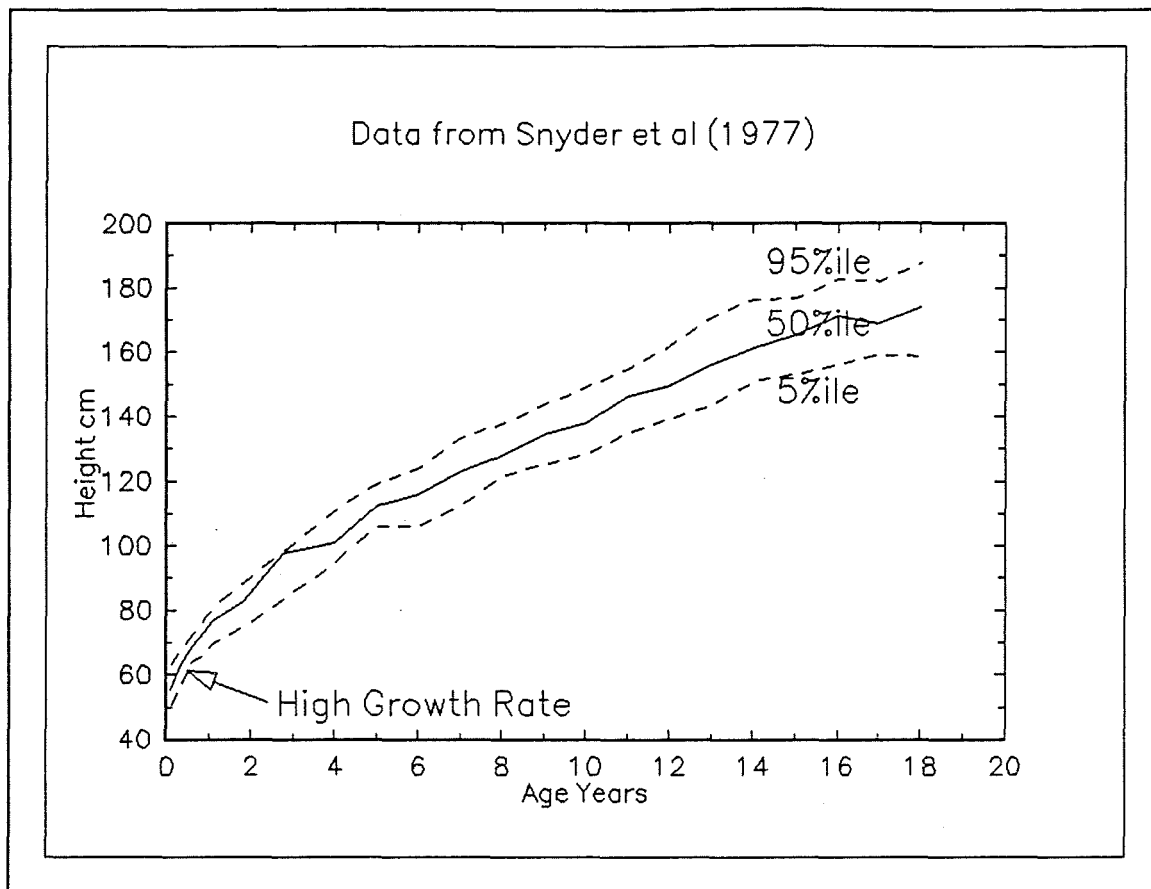
double in mass in this period, and the child restraint must be designed to encompass this large change in size.



**Figure 3.12** Variation of mass with child age

At a given age children can vary significantly in size and development. For example the 1 year old child mass can vary between 7.5 Kg, at the 5th percentile, to 11.7 Kg at the 95th percentile. This is the reason for the grouping of child restraints by mass rather than age of the child.

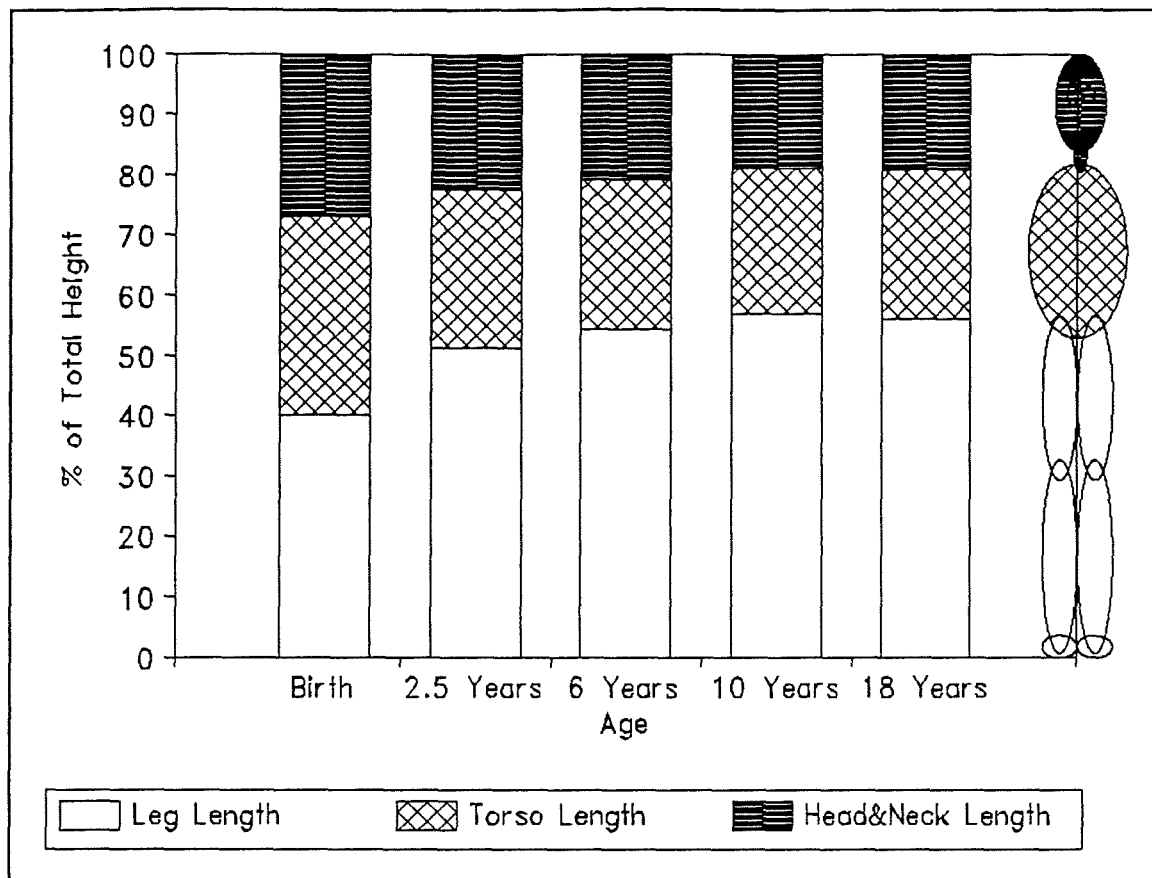
The height of the child also exhibits similar ranges in growth. Figure 3.13 shows the growth of the child in terms of height at a given age. Between 1 and 4 years old the 50th percentile child will grow from around 75 cm in height to 101 cm, a change of 26 cm. The 50th percentile child at birth will be around 50 cm tall. This large range of child size causes many problems for the child restraint designer. The restraint must be large enough for the 4



**Figure 3.13** Child height variation with age

year old child, but the new born or 1 year old child must not be loose in the same seat. In addition the harness anchorages within the restraint must be correctly located for all children. This design requirement leads to the current two or three shoulder harness slot design which we see in current child restraints.

Another major feature of child anthropology is the change of body proportions with age. Figure 3.14 illustrates this feature of child development. It can be seen that the infant at birth has a head and neck region that is relatively much greater in size than is observed in adults (28% compared to 20%). At birth the brain is generally 25% of the adult size, although the body as a whole is only 5% of the adult size. In the first year of life the brain grows rapidly and attains 75% of the mass of the adult brain. Therefore it can be seen that the head region must be a much greater proportion of the total body volume in the child than the

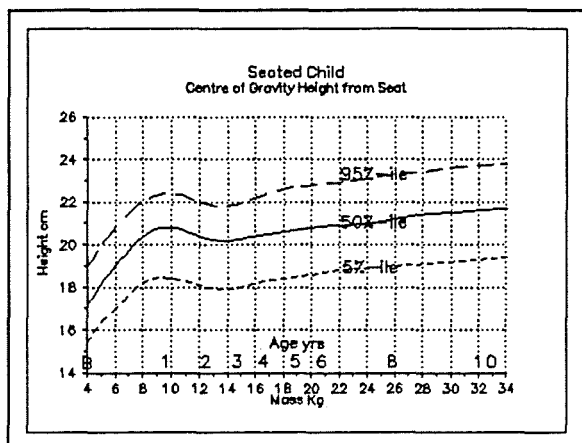


**Figure 3.14** Variation of child body proportions with age.

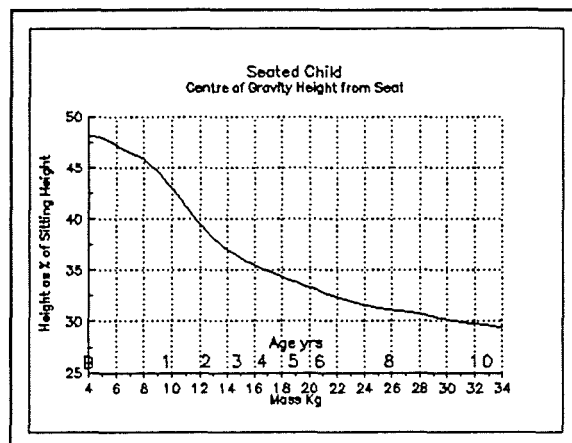
adult. A proportionately larger head area must imply a greater risk of head injury due to impact. The variation of the body proportions also affects the location of the body's centre of gravity.

Figure 3.15 shows the location of the child seated centre of gravity (CG) in the upright seated position, as measured from the seat of the child. The rapid initial growth of the child can be observed as a increase in the CG height. If the seated child CG is shown as a percentage of seated height (see Figure 3.16) it can be seen that at birth the child's CG is located relatively high in it's body (46 % of sitting height). However, as the child develops this relative CG height lowers to around 29 % at age 10. This means that the younger child is more likely to lead with the head in unrestrained movement. This increases the chance of a head injury to unrestrained young children. The change in

position of centre of gravity must be addressed in the design of child restraints, as it will affect the kinematics of the restraint during impact.



**Figure 3.15** Variation of Centre of Gravity with child mass



**Figure 3.16** Centre of Gravity as a proportion of sitting height

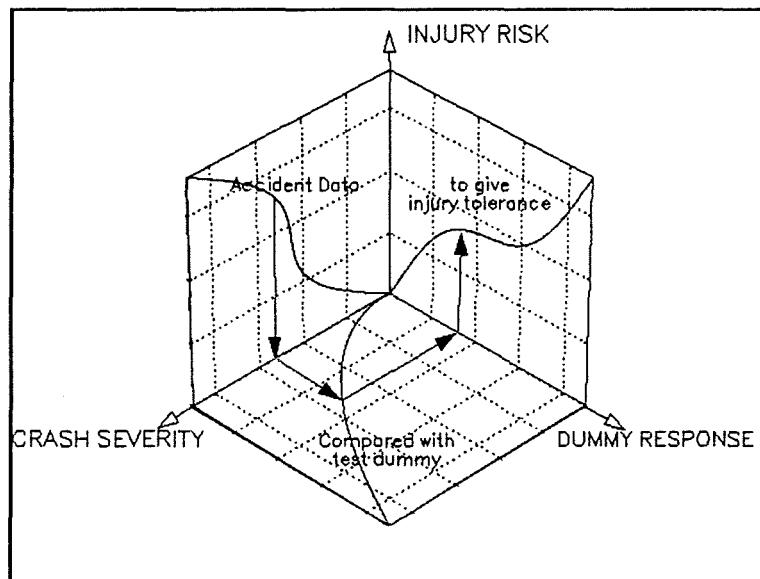
### 3.3 CHILD INJURY TOLERANCE

Traditionally data for creation of injury tolerance levels has been gained in the laboratory. Tests with human surrogates, which can be cadavers, animals or dummies, are conducted and levels of injury are formulated from the observed injuries and results. Also used are human live volunteer tests. However, these are of course at the low level of reversible injury. An important subject and proponent of the volunteer test was Colonel John P Stapp, who has subjected himself to hundreds of survivable impacts.

All of the surrogate tests have disadvantages. Cadavers are probably the closest, in biomechanical terms, to the real human occupant. However, a cadaver does not have the muscle tone and joint stiffness of the live subject and there is a general shortage of usable subjects. Live animals are used in the place of cadavers and obviously this surrogate benefits from having a

wholly live physiology, but of course the animal does not have the same anatomy and physiology as the human. The test dummy or manikin suffers from similar problems to the former two surrogates, in that it is not a human with the same body structure.

Another method of injury tolerance assessment has been in the form of accident analysis. The data from real car accidents is studied, car impact severity estimated and injuries assessed. The injury



**Figure 3.17** Injury tolerance formulation from accident data. After Korner (1989)

to the occupant at a given crash severity is then compared with the response of a test dummy in a similar crash test (see Figure 3.17). The response of the dummy can then be calibrated to yield an injury tolerance level. This system has the obvious advantage of using real car crash data and real people. But there are problems with this method. Human injury tolerance is a complex function of the age, sex, mass, development and health of the person in question. The situation is further complicated by the variety of vehicle accidents which load the body in various manners and directions. The variety of vehicles on the road, together with the huge number of variations in type of car-car and car-object impacts (frontal, side, rear to car, barrier, post etc), means that it is unusual to have two similar and directly comparable crashes. This in turn means that the collection of a statistically representative sample of data is very difficult and

data is generally presented in the form of probability of injury (injury risk). Thus the z axis in Figure 3.17 is labelled as injury risk. Injury risk levels are defined for a given percentage of the population. For example Mertz (1991) states that the injury tolerance levels are defined as shown in Table 3.ii for upper and mid sternal velocity change in a 3 year old Child Airbag Dummy.

**Table 3.ii** Sternal injury criteria for the GM 3 Year Old "Airbag" Dummy, Mertz (1991)

	Injury Assessment Reference Value IARV		
Injury Risk	1% Risk	10% Risk	25% Risk
Upper and Mid Sternal $\delta V$ Km/h for time interval under 4ms	9	16	19

If the dummy in a given test configuration yields a response of an upper sternal velocity change of 16 Km/h. It would mean that 10% of the population of children of that age, were likely to injured. It would not mean that a particular child has a 10% chance of injury, if he were one of the 10% of the "weaker" children he would definitely be injured.

The injury criteria that have been formulated to date will be discussed in the following appropriate sections. It should be noted that these are the criteria as they are known to the author at this point in time, but they are subject to constant review. In addition the dummy or test specimen to which the injury criteria are appropriate, should be carefully noted. As the response of the test specimen will greatly influence the

criterion in question.

### 3.3.1 HEAD INJURY CRITERIA

As discussed earlier the head is the most common fatal injury location and of course any significant head injury is generally considered serious. It is therefore always been considered important to strive towards a valid injury criterion for the head. The first major investigation into head injury criteria was by Lissner et al in 1960. This was in the form of a tolerance curve which was later modified by Patrick et al to become the

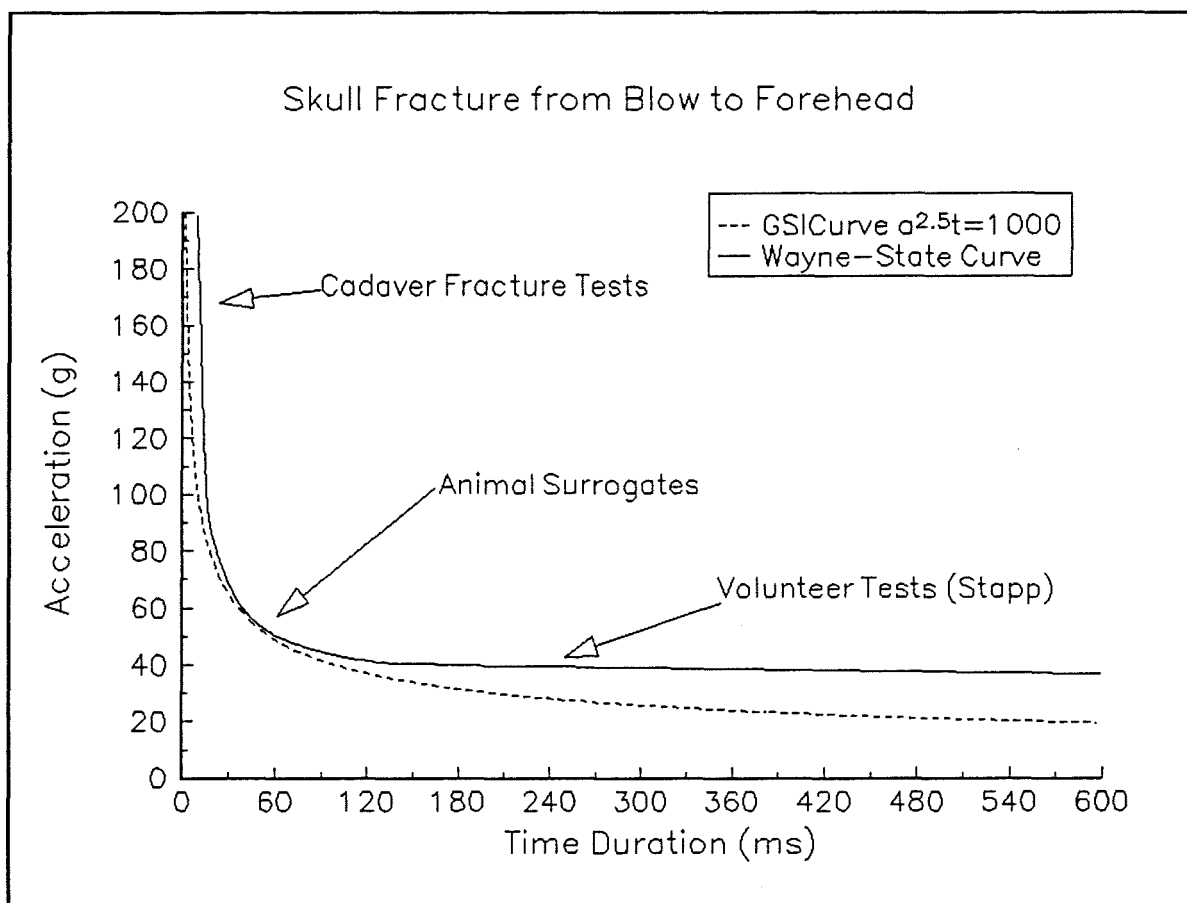


Figure 3.18 Sketch of Wayne State Curve compared with Gadd Severity Index

commonly known Wayne-State Tolerance Curve. This graph, shown in Figure 3.18, represents the human tolerance to head impact as related to effective acceleration and duration of acceleration. The curve was based upon three data sets, human cadaver skull

fracture, live animal tests and live human volunteer tests. The tolerance is defined for adult head impacts with a flat hard surface and predicts serious head injury, such as skull fracture. Also shown in Figure 3.18 is a curve based upon the Gadd severity index. The Gadd Severity Index (GSI) was an attempt to rationalise the Wayne State Curve in the form of an equation (see Equation 3.1).

$$\int_0^T a^{2.5} dt < 1000$$

**Equation 3.1** Gadd Severity Index

The GSI curve is defined for accelerations of time duration between 0.25 and 50 ms, as the GSI curve diverges from the Wayne State Curve at longer time duration pulses (see Figure 3.18). The criterion for injury is that the GSI should not be above 1000.

The Gadd Severity Index has now largely been superseded by the Head Injury Criterion or HIC. HIC is calculated using Equation 3.2. The time window  $t_1$  to  $t_2$  is chosen to maximise the HIC value but is often confined to maximum range of 36 ms.

$$H.I.C = \max(t_2 - t_1) \left( \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right)^{2.5} < 1000$$

**Equation 3.2** The Head Injury Criterion

The HIC was based upon the same data and assumptions as the Wayne State curve, and is purely an assessment of the likelihood of head injury when the head is subjected to a direct blow. It is often misused by applying it to head inertial loads.



Mertz (1991) used comparison of tests and case injuries in the formulation of injury criteria for the GM 3-Year-Old Child "Airbag" Dummy. The injury criteria are defined in the form of Injury Assessment Reference Values (IARV) which are shown in Table 3.iii.

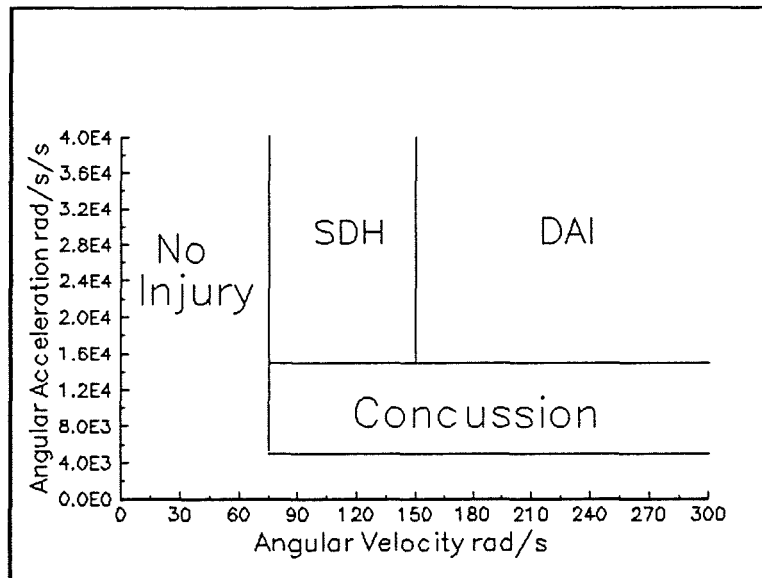
**Table 3.iii** Head injury criteria for the GM 3 Year Old "Airbag" Dummy, from Mertz (1991)

Injury Risk	Injury Assessment Reference Value IARV		
	1% Risk	10% Risk	25% Risk
Head. HIC ( $t_2 - t_1$ ) $\leq 15$ ms	1480	1530	1570

These values are valid for the GM Airbag dummy when used in an evaluation of airbag impact. The criteria are higher than is generally accepted for adult injury ( $HIC < 1000$ ) and there are two possible reasons for this. One, that the head impacts are distributed (ie; airbag contact over a large area of the head, the original HIC was based upon a more concentrated load). Two, that we are considering a child's anatomy, and it may have been found that the child is more tolerant of these type of impacts.

The GSI and HIC tolerance values are proven for head impacts but are generally considered unsuitable for the purpose of assessing non impact injury. They take no account of the direction of acceleration. As discussed in section 3.2.1.1, rotational acceleration is much more important in brain injury than linear acceleration. As such the requirements for a head tolerance must be related to rotational acceleration. The most recent data on this subject was presented by Gennarelli (1992) and is shown as Figure 3.19. This graph relates angular acceleration and angular

velocity to the type of brain injury received. As can be seen an angular velocity of 75 rad/s together with an acceleration of 5000 rad/s<sup>2</sup> is required for the most minor of head injuries, concussion. This data is again defined for adult



**Figure 3.19** Relationship between injury angular acceleration and angular velocity as defined by Gennarelli (1992)

defined for adult injury and it is not known whether a child would be more or less susceptible to such injuries. The brain matter itself will of course be the same in both adults and children, but the shape of the skull differs significantly. The shape of the skull may have an effect on the motion of the brain and therefore the injury received.

It is possible to scale the data that is available for adults to children. The accepted value for adult linear head acceleration tolerance for a direct impact is 80 g for under 3 ms (Taken from the Wayne State Curve). This defined for head impacts with steering wheels or other vehicle interior features. Stürtz (1980) used mechanics of similitude to estimate the child variation from adult tolerance values and formed an equation which is presented here as Equation 3.3.

Using this equation the tolerance for a 3 year old child can be calculated as 86.1 g (based upon adult brain mass 1.36 Kg , 3 year old brain mass 1.09 Kg). Thus the child injury tolerance is

$$a_C = a_A \left( \frac{m_A}{m_C} \right)^{\frac{1}{3}}$$

**Equation 3.3** Relationship between adult and child translational acceleration tolerance limits as defined by Stürtz (1980).

a = acceleration, m = brain mass, subscripts A = Adult C = Child

shown to be slightly higher than for the adult. However we do know that the child skull is weaker and more elastic than the adult which would suggest that tolerance should be lower. Stürtz (ibid) did point out this apparent contradiction.

$$\alpha_H = \alpha_M \left( \frac{m_M}{m_H} \right)^{\frac{2}{3}}$$

**Equation 3.4** Relationship between Human (subscript H) and Monkey (subscript M) rotational acceleration tolerance. Rotational acceleration =  $\alpha$ , Brain mass = m

On the subject of rotational acceleration Stürtz (ibid) utilised the work of Ommaya et al (1967). Ommaya et al formed an equation based upon the earlier work of Holbourn which is similar to the translational equation above. This equation (Equation 3.4) was used by Stürtz (ibid), to scale the rhesus monkey data of Ommaya (ibid) to children. The Tolerance level for a 10 ms rotational acceleration for a 3 year old child was calculated to be 8140 rad/s<sup>2</sup> or for a 3 ms period 81400 rad/s<sup>2</sup>. These figures were defined for non impact accelerations, ie inertially produced and were higher than that calculated for adults (7020 and 70200 rad/s<sup>2</sup> for 10 and 3ms pulses respectively).

The lower limits for adult rotational acceleration tolerance as presented by Gennarelli (1992) are 5,000 rad/s<sup>2</sup> for concussion and 15,000 rad/s<sup>2</sup> for DAI or SDH (see above). Using Equation 3.4 and the masses of the adult and three year old brains as 1.36 and 1.09 respectively, we can scale these two adult tolerance limits as shown in Equation 3.5 and Equation 3.6. As we can see the

$$\alpha_c = 5000 \left( \frac{1.36}{1.09} \right)^{\frac{2}{3}} = 5794 \text{ rad/s}^2$$

**Equation 3.5** Child tolerance to rotational acceleration using equation from Ommaya et al (1967), brain mass data from Stürtz (1980) and adult tolerance from Gennarelli (1992). Defined for a Concussion injury

child tolerance to rotational acceleration is higher than for adults. According to Stürtz the higher tolerance limit for children is to be expected. The mechanism for brain injury in non impact rotational acceleration loading is stated as being ruptures to bridge veins due to shear loading. Stürtz then quotes from another publication<sup>1</sup> stating that the strength of arterial tissue in children is 40% higher than for adults. Thus it should be expected that the tolerance limits for children are higher than those for adults. However, this does not take into account that there are other injury mechanisms that involve damage to the brain matter itself or the different skull shape of the child. Gennarelli (1992) suggests that diffuse axonal injury involves

$$\alpha_c = 15000 \left( \frac{1.36}{1.09} \right)^{\frac{2}{3}} = 17384 \text{ rad/s}^2$$

**Equation 3.6** Child tolerance to rotational acceleration using equation from Ommaya et al (1967), brain mass data from Stürtz (1980) and adult tolerance from Gennarelli (1992). Defined for a SDH or DAI injury

damage to the neurons of the brain. It is not known whether the tolerance for neuron damage is higher for children than adults.

For the time being we must assume that child injury tolerance is the same as for adults, with the exception, perhaps, of impact injuries where the child's softer skull must reduce the child's tolerance levels.

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<sup>1</sup> Yamada.H. Strength of Biological Materials. Williams a. Wilkins Company, Baltimore, USA, 1970.

### 3.3.2 NECK INJURY CRITERIA

This is one of the most unknown areas of occupant injury. There are no generally accepted tolerance levels for the adult neck. The child neck, as was discussed in section 3.2.1.1, is considerably different in structure to the adult neck, therefore no deductions can be drawn from the limited adult knowledge. There are only two tolerance levels for the child neck that are known to the author. One is from Stürtz (1980) and the other from Mertz (1991). From comparison of dummy neck loads and reversible pedestrian neck injuries, Stürtz formed a neck "Protection Criteria (SK0)" of 880 N. The Protection Criteria was defined to be at a level which would prevent all irreversible injuries. This tolerance level is based upon neck loadings in an Aldersen VIP 6c dummy at C7 level, when subjected to pedestrian impacts (ie: direct impact to the head of the subject) and is defined for 6 to 7 year old children. How this loading criteria relates to the TNO P3 dummy used in this investigation is not known to the author.

Mertz (1991) provides a similar format for neck injury criteria as was shown for head injury in the last section (see Table 3.iv). Again these tolerances are based upon the GM 3 year old "Airbag" Dummy involved in an impact test with an airbag.

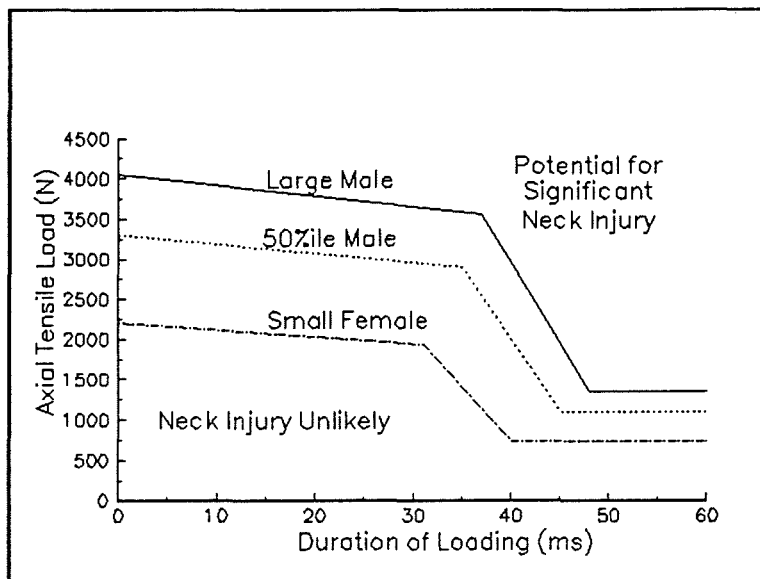
**Table 3.iv** Neck injury criteria for the GM 3 Year Old "Airbag" Dummy, from Mertz (1991)

Injury Risk	Injury Assessment Reference Value IARV		
	1% Risk	10% Risk	25% Risk
Neck Tension (N)	1060	1125	1160

These values appear to be quite high in comparison both with the Stürtz value above (880 N) and the values quoted by Mertz in the

same document for adult injury.

Mertz proposes the injury assessment curves as shown in Figure 3.20. It can be seen that as occupant size decreases, so does the tolerance to impact. The small female, for example,



has a injury assessment value of 734 N for a duration

**Figure 3.20** Injury assessment curves for axial neck tension measured in the Hybrid III adult dummies, as published by Mertz (1991)

of 40 ms, whereas the large male can apparently withstand 1351 N for 48 ms. If the trend in injury levels continues downward through to children, we would expect much lower injury values than are stated for the 3 year "airbag" dummy (Table 3.iv). The Stürtz value would appear to be a more reasonable injury criteria for general use. The high injury criteria seen in the 3 year "Airbag" dummy may be a function of the crash data used for defining the values or the differences in particular dummy responses.

### 3.3.3 THORAX AND ABDOMEN INJURY CRITERIA

Like the skull, the child's rib cage is more flexible than that of the adult. It is conceivable that internal organs can be damaged without rib fracture. Any tolerance criteria must therefore consider this injury mechanism together with the more simple case of rib fracture. The rate of compression of the rib cage also has an effect on the injury sustained by the occupant. Lau and Viano (1986) showed the importance of compression

velocity and have developed the so called Viscous Criterion for Thorax soft tissue injury. Thus the modern thorax injury criterion generally comprises both an acceleration limit and a deflection or velocity limit.

The current standard for testing child restraints in Europe is ECE Regulation 44 (1980). This standard defines the TNO P series dummies which have a stiff thorax with no ability for deflection or compression velocity measurement. The only injury criteria in this standard is defined by way of an acceleration limit of 55g resultant and 30 g vertical component. This level of acceleration is generally accepted as a conservative estimate of injury tolerance. Dejeammes et al (1984) quote, on the basis of cadaver experiments, "conservative deceleration levels" as being from 50 - 80 g.

Both an acceleration and velocity limits are defined for the GM 3 year old "Airbag" dummy as documented by Mertz (1991). These limits are shown in Table 3.v. The upper spine accelerations are comparable with the accepted values of around 50 - 60 g.

Stürtz (1980) also provides a deceleration limit of 55 g for "complete protection against irreversible injuries". In addition Stürtz provides a breaking load for a blunt impact to the 1<sup>st</sup> to 7<sup>th</sup> ribs of 1.6 KN.

#### **3.3.4 LOWER EXTREMITY INJURY CRITERIA**

This injury type was not considered in this project, but known tolerance levels will be discussed. Dejeammes et al (1984) states that, from a review of published literature, "On the whole, the child's bone strength is known to be higher than that

**Table 3.v Thorax and Abdomen Injury Assessment Reference Values for the GM 3 year old "Airbag" dummy from Mertz (1991)**

Body Region		IARV		
		1% Risk	10% Risk	25% Risk
Thorax $\delta t \leq 4\text{ms}$	Upper Spine Acc (g)	55	59	62
	Upper & Mid Sternal $\delta V$ (km/h)	9	16	19
Abdomen $\delta t \leq 4\text{ms}$	Lower Spine Acc (g)	34	42	45
	Lower Sternal $\delta V$ (km/h)	19.5	19.9	20.4

of adults". Stürtz (1991) puts a value on the axial quasi-static fracture of 870 N for a 3 year old child femur. Dynamically Stürtz assumes a multiplication factor of 1.2 and calculates a dynamic axial femur fracture criteria of 1000 N. The actual fracture load is translated in terms of a modified Aldersen VIP 6c dummy response to a load of 800 N (6 year old dummy).



#### 4 LITERATURE SURVEY

#### 4 LITERATURE SURVEY

This survey documents the work of other authors and shows the need for this particular project. Also shown are other areas of information which require further investigation. The literature study will be presented in appropriate sections, starting with a summary of the international standards which are applicable to framed child seats (FCS). This will be followed by the literature on child restraint use, misuse and restraints under test.

##### 4.1 INTERNATIONAL STANDARDS FOR THE APPROVAL OF FRAMED CHILD SEATS

The standards that are known to the author and specifically cover the type of child seat that is the subject of this project are as follows:

- BS3254:Part 2:1988 - BRITISH STANDARD. Seat belt assemblies for motor vehicles. Part 2. Specification for restraining devices for children. 1988.
- BS3254:Part 2:1992 - BRITISH STANDARD. Seat belt assemblies for motor vehicles. Part 2. Specification for restraining devices for children. 1991.
- ECE R44 - ECONOMIC COMMISSION FOR EUROPE. Regulation No. 44. Uniform provisions concerning the approval of restraining devices for child occupants of power-driven vehicles. ("Child Restraint"). 1981. Updated Several times since this date.
- FMVSS 213 - FEDERAL MOTOR VEHICLE SAFETY STANDARD 213. (USA). Child restraint systems. 1990 Edition.
- JIS D 0401 - 1990 - JAPANESE INDUSTRIAL STANDARD. Child Restraints for Automobiles. 1990.

- |              |   |  |
|--------------|---|--|
| AS 1754-1989 | - | AUSTRALIAN STANDARD 1754-1989. Child restraint systems for use in motor vehicles. Part 1-General requirements. Part 4-Type B child restraints (forward-facing chair with harness). AS 3629-1989 is referenced for testing procedure. |
| NZ 5411:1982 | - | NEW ZEALAND STANDARD 5411:1982. Specification for CHILD-RESTRAINING DEVICES IN MOTOR VEHICLES. 1982.   |

The European standard (ECE R44) is now accepted by most of the members of the European community. The following countries have applied ECE R44; United Kingdom, France, Netherlands, Sweden, Denmark, Belgium, Czechoslovakia, Romania, Germany, Luxembourg, Austria, Norway, Hungary and Italy. Thus although many of the individual countries' standards are still in existence, they are not presented here. The only exception to this is the British standard.

The standards are similar in many respects. However there are some differences that will be discussed in the following two sections. The first section will deal with the design limits that are imposed on child restraints, whereas the second section will deal with the differences in dynamic approval testing.

#### 4.1.1 DESIGN SPECIFICATIONS FOR CHILD RESTRAINTS AS DEFINED BY THE STANDARDS<sup>1</sup>

The design specifications of the various standards are summarised in Table 4.i. One of the most important differences between the standards is in the specification of the harness. Since the 1988 revision, the British standard (BS3254:Part2) has required a full five point harness. This includes a crotch strap which is

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<sup>1</sup> Details are only given for the applicable CR type. Many of the standards cover wider CR ranges.

essential in the prevention of submarining. Of the other international standards, all effectively specify a crotch strap, with the exception of the Japanese standard.

**Table 4.i** CR design requirements as defined in international standards.

STANDARD	CHILD MASS RANGE	HARNESS TYPE	WEBBING SIZE	CR SIZE LIMITS	BUCKLE RELEASE LOAD
BS3254:Part2: 1988	9 - 18 Kg (Group A)	5 Point with Crotch strap	Width greater than 25mm	None	> 30 N (No tension test)
BS3254:Part2: 1992	As Above	As Above	As Above	None	As Above
ECE R44:1980	9 - 18 Kg (Group 1)	As Above	As Above	500mm High seat back	> 40 N (No tension test)
FMVSS 213:1990	>20 lbs (9 Kg)	As Above	Width greater than 1.5" (38mm)	20" High seat back (508mm)	9 < lbs < 14 (40 < N < 62) 2lb tens test
JIS D 0401:1990	9 - 18 Kg (Grade W2)	No specified type	Width greater than 25mm	500mm High seat back	> 10 N (No tension test)
AS 1754.4-1989	8 - 18 Kg	Not less than 3 Point	Contact area greater than 20175mm <sup>2</sup>	Defined harness slot positions	40 < N < 80 (No tension test)
NZS 5411:1982	9 - 19 Kg (CR Type B)	Effectively 5 Point.	Width greater than 30mm	None	Buckle must release under 180 N load

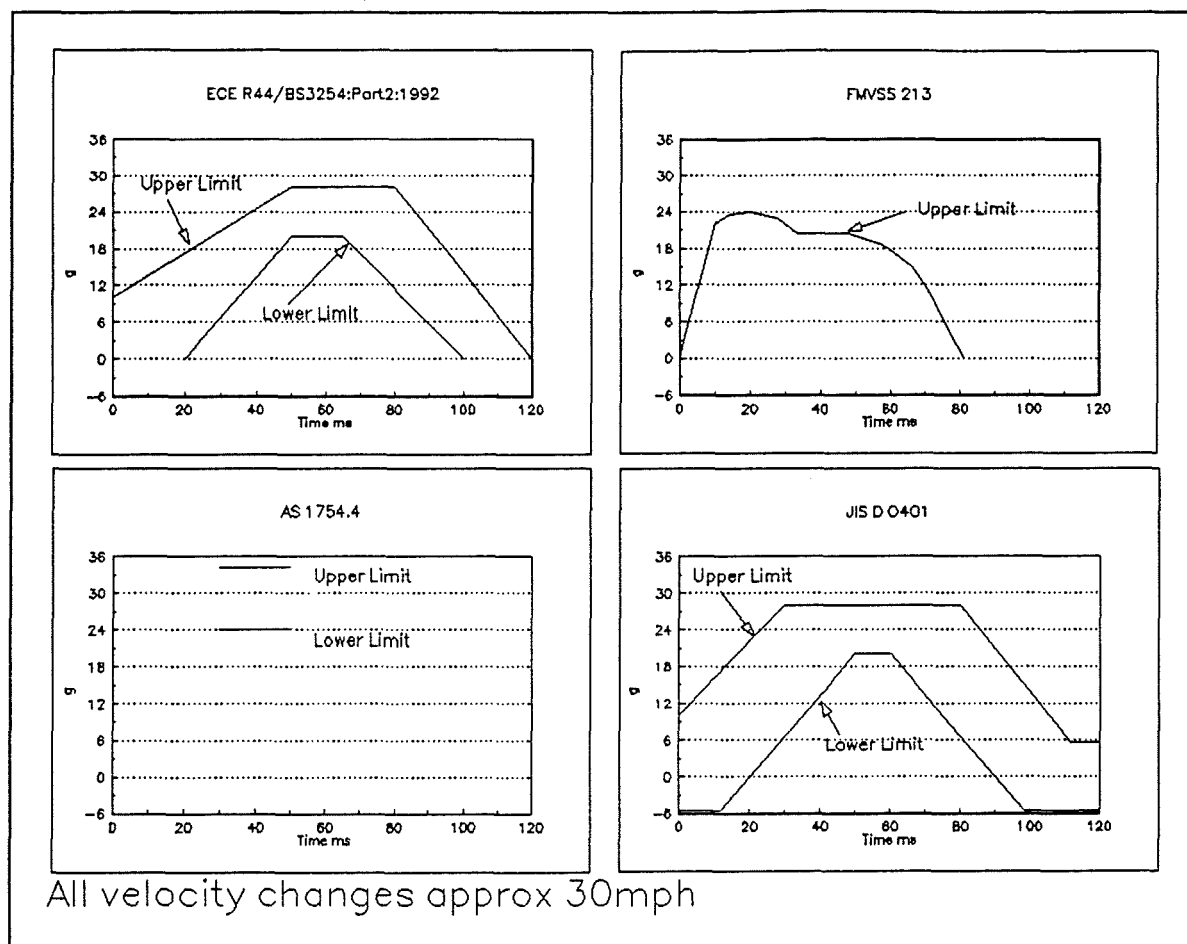
Most of the other design specifications are very similar throughout the various standards, excepting the buckle release load. The allowable buckle release load varies from 10 to 180 N in the standards shown. The problem in defining a release load, is that the load must be low enough to allow emergency release by a person of low strength after an impact when the harness will be loaded, yet high enough to stop the child from releasing itself when the harness is not loaded. The range of release loads shown in the table, reflects the differences in opinion of the various standards bodies on the importance of the two defining factors.

On the whole the standards' committees are united on the grouping of the child age ranges, and thus many of the dimensional specifications are similar. The most common dimension that is specified is the height of the seat back. This is defined to be high enough to act as a head restraint for the child in rebound, and thus reduce hyperextension injury (Whiplash). Webbing width is also given a minimum dimension, so as to ensure that the restraining load is spread over an appropriate area. This is to reduce the probability of direct loading injuries.

#### 4.1.2 DYNAMIC TESTING OF FRAMED CHILD SEATS

The basic test procedure is similar throughout the standards. The child seat is placed on a standard test seat, which is in turn anchored to a dynamic rig. A dummy is placed in the child seat to represent the child occupant. The child seat is then fitted according to the manufacturers specification, with perhaps some slack included in the harness and anchorages to represent a more common use scenerio. The rig is then decelerated from a given velocity (around 30mph or 50 kmph for a frontal impact). The pulse shape of the sled deceleration is generally required to either conform to a given envelope shape or a given mean value. The former must be considered preferable, as the shape of the vehicle deceleration pulse affects the dynamic performance of the child restraint (see 10.6). The pulse shapes that are defined in a standard are shown in Figure 4.1.

One unusual feature of a standard which should be noted is the hinged seat back in BS3254:Part 2. The adult test seat has a heavy back which is hinged at the base and allowed to pivot forward during the test. This adds additional loading on the child seat.



**Figure 4.1** Dynamic test deceleration envelopes for frontal impact

The kinematics of the dummy are recorded using a high speed camera, generally running at 500 frames per second. In most cases the head and/or chest decelerations are also measured. Limits are generally set on the dummy displacement, which is measured from the film recording, and the decelerations of the dummy. The standard will also specify that no load bearing or structural component of the child restraint may fail. Distortion of the restraint is allowed. Some features of the dynamic tests of the various standards are summarised in Table 4.ii.

The most unusual of the standards, in respect of dynamic testing, is that of New Zealand (NZ 5411:1982). This standard requires the child restraint to be dynamically tested in three impact directions, but has no limits for dummy excursions or

**Table 4.ii Dynamic test requirements of various standards**

STANDARD	DUMMY USED	IMPACT DIRECTION	HEAD EXCURSION	KNEE EXCURSION	HIC	HEAD ACCEL	CHEST ACCEL
BS3254:Part2: 1988	TNO P3 15 Kg	FRONTAL	600 mm	-	-	-	-
BS3254:Part2: 1992	TNO P3 15 Kg	FRONTAL	500 mm *	-	-	-	60 g
ECE R44:1980	TNO P3 15 Kg	FRONTAL	550 mm	-	-	-	55g(30 z)
		REAR	-	-	-	-	-
FMVSS 213:1990	Part 572 15 Kg	FRONTAL	813 mm #	914 mm #	1000	-	60 g
JIS D 0401 1990	9 & 15 Kg	FRONTAL	600 mm	700 mm	-	80 g	60 g
AS 1754.4-1989	TNO P6 22 Kg	FRONTAL	550 mm	-	-	-	-
		SIDE	-	-	-	-	-
		REAR	-	-	-	-	-
NZS 5411:1982	Taru Simon 8 & 21.5 Kg	FRONTAL	-	-	-	-	-
		SIDE	-	-	-	-	-
		REAR	-	-	-	-	-

\* Limit of 600mm with any top tether removed  
# Converted from inches. Measured from SORL

accelerations. The New Zealand standard in addition to the dynamic test requirement, has a static test with a head excursion of 500 mm. New Zealand is currently in the process of altering this standard, and has a view to possibly adopting the Australian standard.

All of the other standards have an head excursion limit of between 500 and 600 mm, when subjected to a frontal impact, with the exception of the United States of America (FMVSS 213:1990). The head excursion is a measure of the likelihood of a head impact on the car structure and is generally a limit placed upon the movement of the head relative to a fixed point on the test seat. FMVSS 213 sets a higher limit, which reflects the larger

size of most American automobiles. The American and the Japanese standards also set a limit for knee excursion, which is an attempt to reduce lower limb injury and reduce submarining.

The excursion limit set in the British, European and Japanese standards is considered by many people, to be too high. Pincemaille et al (1991) conducted a study of car geometry, and showed that the majority of French cars have a distance to front seat, of less than 500mm. In fact an excursion limit of 400mm would be necessary to minimise the risk of head injury.

The other limits that are set in the standards are based upon the biomechanical injury tolerance limits of the child, as they are known at this point in time. There is a general consensus that a dummy deceleration of 55 to 60 g, represents the lower limit of injury as would occur in a child. In addition to this limit there is a 30 g limit imposed on the vertical axis deceleration, in the European ECE R44 standard.

Head acceleration is only considered in two of the standards studied here. The American FMVSS 213 standard imposes a limit of 80g on the head acceleration, whereas the Japanese standard uses a Head Injury Criterion (HIC) value of 1000. Both these values are based on adult injury criteria. There is a definite need for child injury based criteria for the head and neck, to replace the limits that are currently used.

Both the New Zealand and the Australian (AS1754.4) standards' are atypical in that they require the use of a dummy of around 22 Kg. This is a child mass which is outside of the child seat design specification, and would in real life be a misuse situation. This



test configuration will induce test loads on the child restraint that are higher than would occur in actual use.

#### **4.2 CHILD RESTRAINT USE AND MISUSE**

Child restraints can be designed that afford excellent protection for the occupant in a crash of the severity of the 50 Km/h test. However, parents must be persuaded first to obtain and secondly to use the child restraint. Once in a 'real life' situation the child restraint is also often misused, which limits the effectiveness of the restraint. This section of the study will concentrate on the factors influencing the use and misuse of child restraints.

##### **4.2.1 FACTORS AFFECTING CHILD RESTRAINT USE**

One of the most comprehensive studies on child restraint use and misuse is that published by Wagenaar et al (1986) and summarised by the same authors in Wagenaar et al (1988). This study attempts to link the use and misuse of child restraints with various demographic, social, health, behavioural and educational factors. The survey was conducted by observation followed up by personal interviews and mail-back questionnaires, and was based in the state of Michigan (USA). A study based on earlier data was published by Haaga (1986). This study was based upon the results of a National Health Interview Survey (USA) that was conducted in 1981. Thus this study may be considered as more representative of the US population, although it is less comprehensive. Both of these studies will be frequently referenced in the following two sections which consider the various types of factors and report data which includes the use of seat belts as well as child seats.

A study published by Weber and Allen (1982), allowed 32 sets of

parents to choose and then use a selection of child seats, and then studied the changes in parent opinion and usage of the seats. An essay was produced by Prior-Hansen (1976) which deals with some of the psychological aspects of child restraint use.

#### **4.2.1.1 SOCIODEMOGRAPHIC FACTORS**

The age of the child car occupant appears to have an influence on the restraint of the child. Wagenaar et al (ibid) observed that restraint usage decreased over the age range of the sample (91.7% at under 1 compared with 71.2% at 3 to 5 years). This is supported by the findings of Haaga (ibid) who observed a 64.7% usage rate for the under 1 year compared with 13.6 % use for the 6 year olds. The difference in the actual usage rates for a particular age of child in the two studies, reflects the sample location, method of survey and the times of the surveys. A study of accident data in Sweden by Carlsson et al (1987) also revealed a similar restraint use pattern. Approximately 53% of under ones were restrained (80% if carry-cots are included), compared with 46% of 1 - 3 years and 31 % of 4 - 6 years. Since this time restraint use in Sweden has increased, and a rate of 80 % for the under 6 year range was reported by Turbell (1989). In the Swedish case the age related usage rate may be a function of an infant seat loan scheme which was introduced in 1983. In itself the loan scheme would induce a much higher usage rate for the under 1 year group, but also as the children grow the parents are more used to having to restrain their child. Another reason for decreasing child restraint usage may be the perceived fragility of the child, which would decrease with age. The findings of these publications is also supported by Krüger (1989), who showed a similarly decreasing seat usage from approximately 80% at 1 year to 50% at 4 years.

Wagenaar et al (ibid) did not measure a difference in misuse rates with age of child. Misuse generally remained constant with the age of the child at a level of about 65%.

The sex of the child or car driver were shown to have little effect on the usage rate in the document produced by Wagenaar et al.

The family income or lack of it is often used as an argument against compulsory child seat use. To some extent this is supported by the findings of both the aforementioned publications. Restraint usage is shown to increase with income, for both child seats and seat belts. However this rise in restraint use could also be attributed to educational level, which would be related to income.

The educational level of the parents/driver of the child occupant is shown to be proportional to the rate of child restraint use. Haaga (ibid) reported that if the household head had an education to a level below high school graduate, the child was half as likely to be restrained in transit when compared with a family of education higher than high school. Wagenaar et al (ibid) reported usage rates of 80 % for high school graduate or less, and a rate of 92.8% for a family with some post graduate education.

Health promotion behaviors were studied in both the USA papers mentioned above. The family health behaviour was related to smoking during pregnancy and breastfeeding in the national health survey documented by Haaga (ibid). Whereas Wagenaar et al (ibid) related general smoking and last dental visit to restraint usage.

There is a general relationship shown in both documents that families which have a better health related behavior have a higher child restraint usage. In Haaga it is shown that if the child was breastfed he is 50% more likely to be restrained. Similarly if the mother did not smoke during pregnancy the child was 15% more likely to be restrained. Wagenaar et al reported a general increase in restraint with health behavior. Restraint by parents who never smoked was measured at 86.7% compared with 79.5% for parents who smoked at the time of the survey. Also families who reported a dental visit within the last 6 months registered a 87.6% restraint usage whereas parents who reported that the last dental visit was more than 2 years ago exhibited a 78.3% restraint use. The only health behavior factor which disagrees with these findings is among those people who do smoke. In a sample of parents who do smoke, Wagenaar et al reported a slight increase in restraint use with the number of cigarettes smoked, no explanation is given.

In general the children of families in a higher social grouping are more frequently restrained. Another factor which was studied in both Haaga and Wagenaar et al was the ethnic group of the parents. In both studies large differences were noted between the restraint of children in the white ethnic group, to those in the non-white groups (Wagenaar et al; White 80.9% usage. non-white 44.6% usage). In the USA, as in many western countries, persons in the non-white ethnic group tend to be in the lower social group and therefore are often families with lower levels of education, income and health behavior. Thus the differences between restraint usage in ethnic groups, may reflect the differences in social factors rather than ethnic practices.

All of the social factors that are discussed above are interlinked, and thus it is very difficult to attribute any one factor which is responsible for reducing restraint use. However, studies such as those discussed here can identify social groups to which restraint usage improvement programmes should be directed.

#### 4.2.1.2 THE PROMOTION OF RESTRAINT USE

The promotion of child restraint use can generally be conducted in one of three ways; Introduction of loan schemes, improvement of road safety education or by legal requirements. There are arguments for and against each of these methods and some evidence to support the arguments. Work which has analysed the relative merits of the three methods will be discussed in this section of the thesis.

##### Legislation

Lowne et al (1984) observed the use of adult belts and child restraints by children in the UK, before and after the introduction of the front seat adult belt law in January 1983. It was observed that this law had a relatively minor effect on restraint usage. The restraint usage in front seats for large children was increased, and the percentage of restraint for babies in the rear seats was increased from 25.8 to 45 %. However the percentage of restrained small children (1-4 years) was decreased from 34.9 to 25.6 %. Overall Restraint usage by children was not altered significantly; usage was 26.2% before and 26.8% after legislation. This illustrates the relative ineffectiveness of adult seat belt law on child restraint use, even though public awareness of road safety must be increased.

A study was conducted by Partyka (1989) on the "Effect of Child Occupant Protection Laws on Fatalities". Estimates were made of the number of children saved by a restraint system in a particular state, over a period of 4 years. States with and without child occupant protection laws were compared and it was estimated that, 19 percent of those that would have been killed (if no one used a belt) were saved in states that did have laws, compared with 10 percent in states without laws. This does indicate a direct positive effect of the occupant protection law.

Lawless and Siani (1984) summarised several usage rate and injury studies. In all cases child restraint usage was shown to increase. However especially encouraging results were seen in states which imposed legislation. Observations in Kentucky exhibited an increase from 14.4% before to 22.7% after the law. In North Carolina a restraint law was introduced in 1982, restraint use increased from 27 to 41% and fatalities decreased from 1.7% to 1.0%. Both these cases illustrate the apparent effectiveness of legislation. It was noted in this document, that implementation of the law was not in itself enough to increase restraint use. The public must also be informed of the law and the law must be enforced. It was recommended that enforcement of the law would be more effective if the Police (whom must conduct the enforcement) were educated in the need for the legislation.

To some extent the legislative method of increasing child restraint use, is supported by Wagenaar (1986, *ibid*). In a survey of restraint use it was noted that 78.6% of people who were aware of a child restraint law restrained their children, compared with 61.8% who were unaware of the law. However it does not appear that fear of prosecution is the driving factor behind this

difference. One question in the survey asked if the vehicle drivers were influenced by the "fear of ticket". Analysis of the answers to this question actually showed a reduction in restraint use as influence increased. This may suggest that the introduction of a law educates rather than threatens parents into restraining their children.

Hietko et al (1983) showed, in a study of the effect of loan schemes on misuse, that legislation increased child restraint usage in Michigan, USA. The two samples that they studied were taken before and after a law was enacted. The samples were split into rental consumers and non-rental. Of the rental consumers, 82.5% were using a restraint before the law and 85.5% after. In the other much larger group, 38.8% used restraints before the law compared with 55.7% post law.

In the UK, legislation on the use of child restraints has been enacted. The Motor Vehicles (Wearing of rear seat belts by children) Regulation 1989, was introduced in September 1989 for the protection of children. However, this regulation only insists on the restraint of the child, if an appropriate restraint is installed in the vehicle. An "appropriate" restraint is defined for different age groups as follows;

under 1 year: A restrained carry cot or infant seat.

1 - 4 years: A child seat or adult belt and booster cushion.

4 - 14 years: An adult seat belt with or without booster.

There are obvious deficiencies in this legislation. It is not generally recommended that a child under 8 or 9 years uses a seat belt without a booster cushion, although it is probably better than nothing. In addition, a child of under 4 years is not best

protected in a seat belt and booster cushion, and if no such cushion or safety seat is available the child is not required to be restrained at all. Another problem with this legislation is that it is not generally enforced and little information is available to the parent on the suitability of different restraints. This all adds up to a rather ineffectual law, and certainly the author would like to see a much more stringent statute for the protection of children in the UK.

Education and Loan schemes could be seen as the main contributor to the increases in child restraint that are reported in Turbell (1989). Usage rates are shown to increase from 18% in 1983 to 69% in 1987. During this period in Sweden there were belt promotion campaigns and loan schemes introduced as well as some legislation governing the use of seat belts by adults. If the observations made by Lowne et al (ibid) are considered to hold true in Sweden, Then the reason for this increase could be attributed to purely the education and loan schemes.

In General both loan schemes and legislation can provide a good method of directing education to the correct section of the population. If fully enforced, legislation can also induce people to use restraints even if they do not agree with the use or understand the need. The problem with legislation which is not enforced and has little publicity, is that it is ineffectual. In addition a public which is forced into child seat use with no back up information is likely to be a catalyst for large scale misuse. The scale of the misuse problem and its effects are the subject of the next two sections of this thesis.



#### 4.2.2 CHILD RESTRAINT MISUSE

Misuse of child restraints is one of the largest causes of preventable fatalities amongst restrained children involved in car crashes, as will be shown in section 4.2.2.2. This section of the literature survey will deal with the extent, the causes and the effects of the misuse problem.

##### 4.2.2.1 THE EXTENT OF CHILD RESTRAINT MISUSE

The extent of misuse is largely unknown in the UK child restraint population. There has been no recent unbiased study of the rate of misuse of British child restraints. However in 1990 the BBC's "Watchdog" television programme initiated a Child Car Seat Check Day, in which concerned parents could bring their fitted child seats for checking by supposedly trained staff. Observations on the misuse of the child seats were made and the results of these observations were collated by the Education Section, of the British Standards Institution (BSI Education Occasional Paper 5, June 1991). The overall calculated misuse of child seats from this data was 52%. The child seats designed for the 1-4 year age range exhibited a higher misuse rate of 59.4%. It must be remembered when examining this data that this was not an unbiased sample. The sample was self-selecting in that people chose to go to the checking locations. This does mean that the sample will include some people who know they have problems, and thus the misuse rate observed may be higher than the actual case. But also, the sample included concerned parents whom may be the sample of the population who take more care over the child seat fitting, and just wanted to be sure. The accuracy of the results was also affected by the inexperience of many of the technical experts. It is possible that the "experts" missed some modes of misuse.

A similar checking day was carried out by staff of the Middlesex University Road Safety Engineering Laboratory, on behalf of Bedfordshire County Council in March 1991. This data together with other individual checks made at RSEL yields a much higher misuse rate. Framed child seats were observed to have a misuse rate of 93%, Infant carriers 86%, 2/4 point seats 92% and booster seats only 9% misuse. This sample is definitely biased towards misuse, but the observations are accurate. All modes of misuse were included and maladjustment of the harness was noted as the chief mode (57% of framed seats). This study is first published in this document as Chapter 12. Using the results from the last two samples, a misuse rate of 70-80% could be considered a reasonable estimate.

Unbiased studies of misuse have been conducted in other countries. In a summary of the USA survey reported fully by Wagenaar (1986, *ibid*), Margolis (1988) stated that of the children in child restraint devices, 62.9% were incorrectly restrained. The mode of misuse varied greatly. 80% of the seats which required a top tether, did not have the top tether installed, in addition 50% of the top tethers which were used, were misused. Locking clips were also a major misuse mode, with 81.8% of them not used. The other major area of misuse was observed to be the incorrect configuration of convertible (two way) seats. For the infant child this type of seat is designed to be used in a rearward facing configuration, however 85% of those seen in the survey were in a forward facing configuration. This study was conducted by trained observers and analysed by recognised experts in the child restraint profession, thus these figures can be considered an accurate measure of the restraint misuse in the collected sample.

Another survey of misuse in the USA was reported by Bull et al (1988). The survey was conducted over a period of two years 1983 - 84 by trained observers in entrances to Indiana shopping malls. A misuse rate of 73% was observed in the 1983 sample and 76% in the 1984 sample. Infant seats were misused more often (82%) than convertible/toddler seats (74%), which is somewhat surprising. It would be logical to assume that the more complicated convertible seats would be misused more often than the simpler infant seats, as they have more modes of misuse. However the results of this survey do not substantiate this theory. The largest misuse mode was non use of top tethers, which was measured at 57%.

A further USA misuse survey published by Shelness and Jewett (1983) encompassed a larger and wider sample of 3447 child restraints in 12 US states. The overall child restraint device misuse rate was measured at 75% with higher rates for some of the frame type child restraints. For example the Strolee Wee Care seat had a belt or tether misuse rate of 89%. Non use of a top tether was again shown to be a high misuse mode, with a value of 68.5%.

Two studies were reported by Nygren et al (1987) which were concerned with the level and type of misuse in Sweden. The Swedish child restraint design differs substantially from the general European in that up to 4 years children are restrained in a rearward facing configuration. Thus the results of these surveys are not directly comparable with the others mentioned here. The overall misuse rates are given as 40.9% for the first major study and 65.1% for the follow up study. The studies were conducted at two different sites and the difference in misuse rates reflect the different population samples. It can be seen

from these results that misuse is a common problem even in Sweden, which is generally regarded as a setter of standards in road safety.

The next section of this document will explain why misuse is such a problem, by examining the effects of misuse.

#### 4.2.2.2 THE EFFECTS OF MISUSE

The effects of child restraint misuse are twofold. Firstly there is the obvious effect on the dynamic performance of the restraint and the increase in injury potential to the child. The degradation of performance can be as little as a slightly higher deceleration of the occupant (where the restraint is still reducing injury risk) to an actual additional threat to the child involved in an accident (Gross misuse). The latter case could be a situation where the restraint is not actually anchored to the vehicle. When the child/seat impact with a surface in the vehicle, the child will have an additional weight (child seat) and thus higher injury potential than if not restrained.

The second effect of misuse is less obvious, and that is the effect on the perceived effectiveness of restraints. This secondary effect is discussed briefly in Margolis et al (1988, *ibid*). When legislators and the public (via the media) examine the effect of child restraints on child injuries, the apparent protection of restraints is reduced by misuse. Injury surveys are conducted on a large scale with the only restraint parameter being if the occupant was restrained or not. No account is taken of the quality of that restraint. Thus the apparent effectiveness of a restraint can be greatly reduced. This is perfectly illustrated in the injury study published by Vallée et al

(1991). Vallée et al examined the fatal child traffic accident cases reported in France in 1990. No statistical difference in fatality rate was found between unrestrained and restrained children involved in car impacts. This apparent total ineffectiveness in restraints was attributed to misuse, the use of unapproved child seats and a slight bias in the violence of restrained child crashes.

In addition to large scale statistical studies, individual misuse cases are often sensationalised in the media. Cases of restrained child fatality are often published with little or no background information on how the restraint was used. Such cases must have an affect on the public's perception of child restraint effectiveness. Even reports where the misuse is well documented can be misleading. A short report in the British Medical Journal by Ross and Gloyns (1986) carried the title "Failure of Child Safety Seat to Prevent Death" and the abstract contained no reference to misuse. The main body of the report did catalogue the misuse correctly and substantially, however a person may not necessarily read this far into the report. Thus the reader could gain the wrong impression of a well intentioned report, which intended to emphasise the importance of correct fitting.

The subject of the effect of misuse on the dynamic performance of child restraints has been examined in two ways. Firstly by examination of injury cases and secondly by impact test programmes. A single accident case was used to illustrate the seriousness of misuse by Bull et al (1988, *ibid*). An infant was carried in a combination (two way) child seat, in a forward facing rather than the correct rearward facing configuration. In addition the adult belt was routed incorrectly through the frame

of the child restraint and the harness was incorrectly used (the shoulder straps were routed behind the occupant rather than over the shoulder and the crotch strap was not used). During a frontal impact with a tree, the child suffered fatal injuries to the liver from excessive abdominal loading and a slight skull fracture presumably from a head impact.

Lowne et al (1987) examined the "Fatal injuries to restrained children aged 0-4 years, in Great Britain 1972-86". Of the 33 cases that are presented; 21 were injuries sustained by impact with intruding parts of the vehicle, 6 were cases of restraint misuse, 5 were miscellaneous cases of injury from severe or other impacts and 1 was an unexplained fatality. The misuse cases were probably the only cases where the deaths were preventable when considering current car and restraint design, the six cases represent 18% of the fatalities for that period in the UK. Misuse may have been apparent in some of the other cases, but it was not the major cause of injury. Thus the figure of 18% can not be used as a measure of misuse ratio.

One of the misuse cases, that was presented in Lowne et al (ibid), involved slack in the anchorage straps of a two point child seat. Sled tests were used to investigate the possible influence of slack on the restraint performance. Sled tests were performed at speeds of 25mph (estimated velocity of car in case) with and without slack in the straps and harness. For this type of restraint, slack was shown to dramatically increase both the chest deceleration and the head excursion of the dummy. The child in the accident received a fatal neck injury but there was no evidence of head contact. Based upon the test data it was hypothesised that head contact was likely to have occurred.

Gross misuse was the direct cause of at least three of the five injury cases reported in Fuchs et al (1989). The children were seated in the child restraint but not restrained by the integral harness. Thus the children were effectively unrestrained.

In the Safety Study conducted by the National Transportation Safety Board (USA, 1983) on Child Passenger Protection Against Death, Disability and Disfigurement in Motor Vehicle Accidents, 34 accidents were investigated that involved child safety seats. Of these 28 seats were misused. 19 of these seats provided adequate protection for certain accidents or for the accidents in which they were involved. 5 children were killed and 3 injured in misused safety seats, in at least six of these cases the death or injury would have been prevented by a correctly used restraint.

Sled Tests of cases of gross misuse were documented by Ciccone and Jones (1987). Five sled tests were performed with two types of US child seats, a rearward facing infant seat and a forward facing child seat. Two tests were performed with correctly used child seats and then three misuse cases. All misuse cases were of gross misuse in that the harness was not used, and in one case a rearward facing seat was used in a forward facing configuration. The results of the tests are not surprising, the dummies were totally or partially ejected from the seats. Ejection from a child seat would of course mean greater probability of impact injury.

Weber and Melvin (1983) reported on tests of incorrectly restrained framed seats, as well as infant seats and incorrect use of seat belts. The Strolee 599 framed seat was designed for

use with a top tether and was tested first without this tether and secondly without tether and with incorrect adult belt routing. In the first case the child restraint suffered some deformation and the dummy head excursion was excessive. Thus the injury potential to the child would be increased. In the second test the lap belt was routed through the frame at the base of the child seat. This resulted in the failure of child seat at the point where the adult belt was routed and the child seat was then unrestrained. A third test was conducted with a Century 100 with a similar misuse configuration to the second, excepting that this child restraint was designed to be used without a top tether. The results were not as extreme as with the first child seat. Head excursion was increased and thus injury potential to an occupant would be increased.

Kahane et al (1987) used accident hospitalisation data to calibrate the results from misuse sled tests and to calculate the effectiveness of US child restraints. A relationship between test measured HIC/Torso deceleration and hospitalization injuries was formed and used to calculate the effectiveness of correctly used and misused restraints from the test results. The reduction in risk of hospitalization in frontal impact for a child in a correctly used child restraint was given as 61%. Whereas a partially misused restraint only reduced the injury risk by 38%. Thus misuse is shown to increase injury risk.

A new misuse mode has become apparent with the development of airbag systems for adults. Turbell (1991) reported a series of tests conducted in Sweden, where the child restraint was located in a front passenger seat which was equipped with an airbag. The child seats were rearward facing infant and toddler seats as



typically used in Sweden. Chest and head decelerations were seen to be dramatically increased as the airbag deployed behind the child seat. In addition some soft shell (polystyrene) child seats were actually destroyed and the occupants were then effectively unrestrained.

It has been shown that misuse can cause severe reduction in the performance of child restraints. In addition the perceived effectiveness of the restraints is reduced. The following section will deal with the known causes of restraint misuse.

#### 4.2.2.3 CAUSES OF, AND METHODS FOR REDUCING, MISUSE

It has been remarked that the instructions which are supplied with child restraints leave much to be desired. The paper which summarised the "Watchdog" checking day (BSI Education Occasional Paper 5, June 1991) mentioned that poor instructions were a common complaint of the users. This was also true of the smaller sample studied by RSEL staff (see Chapter 12). Langweider & Hummel (1991) reported the results of interviews with child restraint users in Germany. For a sample of users of all types of child restraints; 35.4% of those questioned considered the instructions very good, 58.7% considered them satisfactory and 5.9% considered them very inadequate. In particular the instructions of child seats with a 4 point harness (5 point harness is not common in Germany) were perceived to be poor and required improvement.

The two main other causes of misuse are lack of education and design of restraint and car. Education must address the question of how to correctly fit a child restraint and what level of tension is required in anchorages and harness. The BSI report

(ibid) states that "Consumers typically had little operational criteria for deciding when a restraint was satisfactorily fitted - especially in regard to tension of adult lap and diagonal belts.....". Proof of the importance of education can be observed in Wagenaar et al (ibid). Amongst the many questions in this survey the consumers were asked whether they had received instructions on the fitting of the restraint. Those that received instructions exhibited a correct use level of 37.2%, whereas those who had not, exhibited a correct use level of 16.7%. Consumers who received assistance in installing their restraint also exhibited a higher correct use rate.

Loan Schemes have been shown to reduce the amount of child restraint misuse. Hletko et al (1983, ibid) observed the misuse of child restraints and questioned the parents as to whether or not the child seat was rented. Correct use of rented child seats was measured at a level of 54% (15.9% not restrained). This was compared to a correct use level of 19.4% for child seats that were not rented. These figures were observed in Michigan, USA before the introduction of a child restraint law. After the law was introduced a second sample exhibited slightly different levels. Rented seats were correctly used in 42.1% of the sample whereas the unrented seat correct use rate remained at a similar level (19.7%). The lower correct use in the second rented sample, may reflect the introduction of "forced users" who may have a lesser understanding of the importance of child restraints. Nevertheless the loan scheme is shown to greatly reduce the occurrence of misuse, due to the education received at the time of the restraint supply.

Design is a critical factor in the rate of misuse of a child

restraint. Booster cushions, that are simple to use, have lower misuse rates. In the BSI misuse publication (ibid), booster seats and cushions exhibited a misuse rate of 28.1% whereas child seats were observed to have a 59.4% misuse rate.

The vehicle design also plays an important rôle in the ability of a restraint to be used effectively. Many features of the vehicle that make child restraint fitting more difficult were pointed out by Pincemaille et al (1991, ibid). In recent model vehicles the outboard lap anchorage has been moved forward. This anchorage position has been changed to reduce the occurrence of submarining in the adult. However, this forward anchorage location is approximately 170mm forward of the anchorages used in the approval tests (ECE R44 or BS3254:Part 2:1988) and introduces slack when fitting framed child seats. Pincemaille et al also mention the cushion shape, inertia reel belts and head excursion envelopes as differences between approval tests and actual use situations.

5 TEST AND CRASH VICTIM  
SIMULATION METHODOLOGY

## 5 TEST AND CRASH VICTIM SIMULATION METHODOLOGY

To some extent this chapter is a continuation of Chapter 2, in that it deals with the methodology of crash testing and computer crash victim simulation. However, this chapter will deal with the particular methods used in this project, rather than the more general discussion of Chapter 2. This chapter will be divided into three main sections. The first deals with physical crash testing, whilst the second documents the method of computerised Crash Victim Simulation (CVS). The third section discusses the methods used to assess child seat performance.

### 5.1 CRASH TESTING OF THE FRAMED CHILD SEAT

The experimental crash testing was conducted using the RSEL dynamic test rig as described in Section 2.2.1.1. This section will discuss the actual test methodology together with an assessment of experimental errors.

Most of the time involved in conducting a crash test is involved in setting up of the test and analysing the results. Once the test rig was configured for the correct test type the set up time for an average test was about one hour. This time increased with the complexity of the test. Analysis time again varied with the complexity of the test, but an average time of two hours would be a conservative estimate.

The majority of the child seat tests were conducted utilising a surrogate child seat. This allowed repeatable testing with a single restraint. This surrogate seat is discussed under a separate heading.

### 5.1.1 GENERAL TEST METHODOLOGY

The general test methodology was as documented in the European standard for child restraint testing, ECE R44 (1981). The general specification for the frontal impact test is as follows;

Sled Velocity	48-50 kmph (approx 30 mph)
Sled Deceleration	Peak 20-28 g For envelope see Figure 2.2
Sled Stopping Distance	650 $\pm$ 30 mm

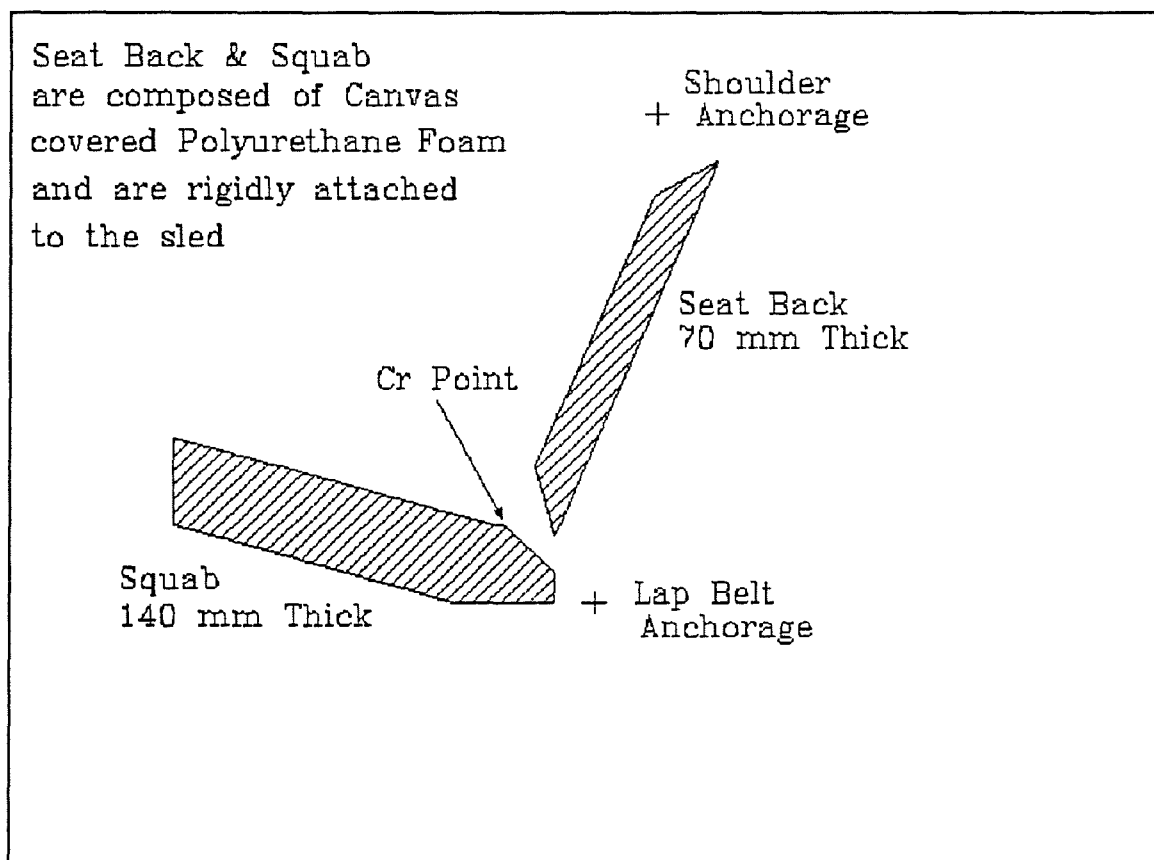


Figure 5.1 Sketch of ECE R44 (1981) test seat

The sled is a flat bed truck, to which one of a number of test seats or car bodies can be attached. The majority of the crash tests, that were performed for this project, utilised the ECE R44 (1981) test seat which is shown in Figure 5.1. The test seat comprises two uniform thickness pieces of polyurethane foam, which represent the seat squab and back. These two sections of foam are rigidly supported on a wood, aluminium and steel structure, which is bolted to the sled truck. There are defined

positions for the belt anchorages, which are generally now considered to be unrepresentative of the average car rear seat. However, for the tests that were conducted under this project, the standard ECE R44 anchorage positions were used.

The framed child seat (FCS) was placed upon the test seat and the test dummy was then put in place. The FCS was then anchored with either a lap or 3 point surrogate belt as required. The surrogate belt was constructed of a single piece of standard seat belt webbing which was anchored using two slot anchor plates. The webbing was threaded through the anchor plate in a manner which did not allow slip and the release of any extra webbing (see Figure 5.2). The seat belt was tightened to what was considered a reasonable level for an average person to achieve. This is a somewhat objective measure, which will vary between test houses. For the purposes of this test programme the level of tightness was assessed by means of a measurement of seat squab crush. This also ensured a repeatable test set up. The level of seat squab crush was set at 50 mm for the FCS surrogate (the FCS surrogate is described in section 5.1.2). Once the 3 point seat belt was tightened, 50 mm of slack was introduced into the diagonal section of the belt. This was done to simulate the reel out from an inertia reel belt. The inertia reel is by far the most common seat belt used in British cars.

The test dummy used in all of these tests was the TNO P3 (50<sup>th</sup> percentile, 3 year old child surrogate). This dummy is defined in both the ECE R44 and the British BS3254:Part2:1992 standards for the testing of child restraints. Both the dummy and the calibration procedure is described in ECE R44 and in the

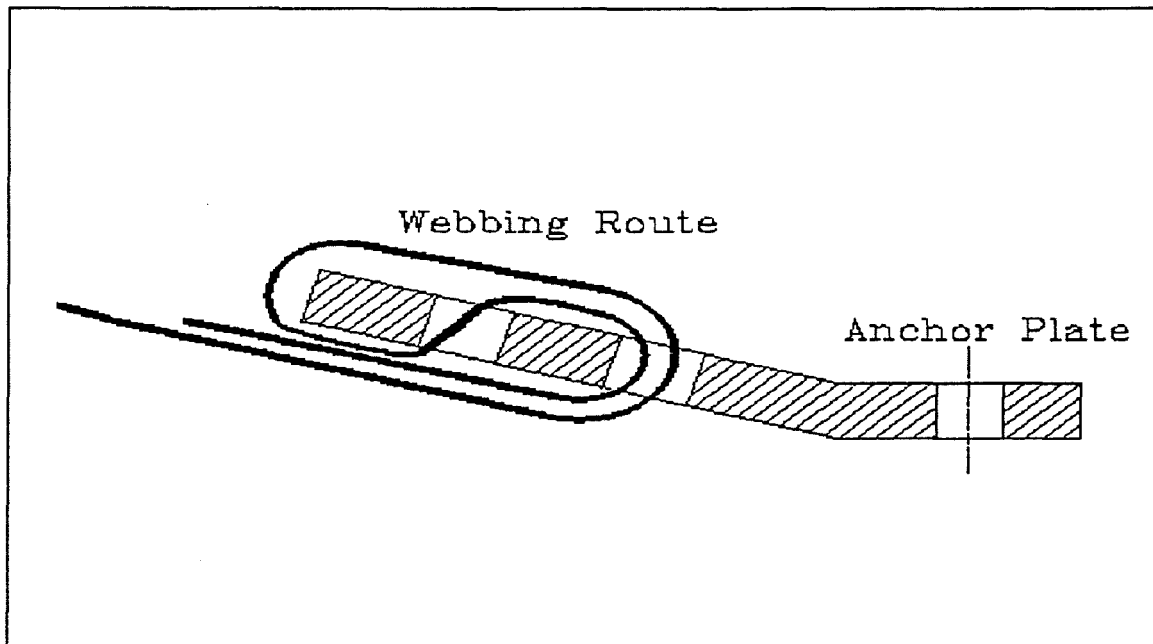


Figure 5.2 Non-Slip threading of surrogate seat belt anchorages

information document supplied with the dummy<sup>1</sup>. In general the dummy was instrumented with a triaxial accelerometer (Endevco 7267A) in both the head and upper torso. There is currently no facility for the measurement of neck loads, lower spine acceleration, chest compression or femur loads. Thus the possibilities for assessment of injury were limited by the dummy's capabilities.

Once the dummy was placed in the FCS and the seat belt tightened, the harness was fitted and adjusted. Unless otherwise stated, it should be assumed that the harness is adjusted in accordance with ECE R44. That is, the harness is tightened around the dummy, with a 25 mm thick pliable board between the dummy's back and the FCS shell. Once the harness is tightened the board is removed. This yields a measured and consistent amount of slack in the FCS harness.

<sup>1</sup> "The T.N.O. Child Dummies". P3/4, P3, P6 & P10. TNO - Rapport. Instituut voor Wegtransportmiddelen TNO. TNO Road-Vehicles Research Institute. Netherlands. Jan 1979.



In several tests additional instrumentation was required. This was particularly the case in those tests which were conducted for the express purpose of validation of the computer model. The additional instrumentation was generally in the form of webbing load cells (manufactured by Denton, Model - BELT) fitted to the child seat harness and the anchoring seat belt. All tests were recorded using either high speed cine film or video, from a point at the side of the sled impact position.

#### 5.1.2 THE SURROGATE FRAMED CHILD RESTRAINT

The surrogate framed child restraint (FCS) was designed for two reasons. Firstly to allow repeatable tests with a single child restraint. This is not possible with a production child seat as there is often some distortion of the frame during a crash test. The surrogate FCS was designed to be rigid in the test environment. The second reason for the surrogate FCS production was to create a framed child restraint which had the capability for changes in design parameters. The first part of this project was concerned with the identification of the design parameters which effect the dynamic performance. This required the creation of a FCS which could be altered in design, rather than creating many different child restraints.

The surrogate child restraint is shown in Figure 5.3. The spatial dimensions for the seat design (shell and feet positions) were taken from a typical production FCS. The typical seat was designated after a survey of the masses of a sample of production FCS. This typical seat was used in the preliminary test phase.

The surrogate FCS was composed of a production plastic seating shell and harness, held within an aluminium frame. The frame

comprised two 6 mm thick aluminium shaped side plates, two 25 mm diameter aluminium tubes and one 25 mm aluminium bar. The side plates were drilled with a series of holes which allowed a variation in position and inclination of the shell, as well as a variation in adult seat belt route. Drawing numbers A1 to A3 illustrate the design of the surrogate and include full dimensions. These drawings together with a table of masses and centre of gravity positions are included as Appendix A.

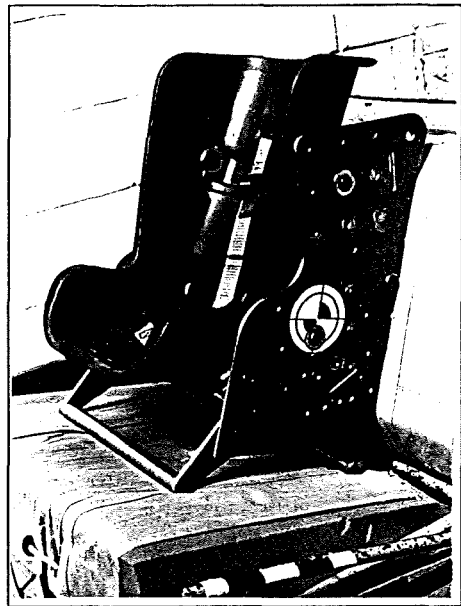


Figure 5.3 Surrogate Framed Child Seat

The surrogate FCS was initially designed with a narrower front leg and an aluminium tube foot as opposed to the solid bar. After initial tests it was obvious that this construction was too weak, as distortion of the frame occurred at this point. The structure was therefore strengthened. The production model plastic shells were as used in the majority of FCS manufactured by KL Jeenay. On average the shell was replaced after 5 tests. This occurred when the shell showed signs of excessive strain or failure around the harness slots. The harnesses were replaced when the webbing exhibited tearing or fraying. This was after an average of 10 tests. The only other component which required occasional repair was the rear bar which fits behind the shell at the upper bolt anchorage. The upper harness straps pass around this bar, it is designed to produce some rigidity of anchorage. This bar was gradually deformed after many tests and required replacement.

### 5.1.3 ACCURACY OF EXPERIMENTAL RESULTS

The accuracy of the experimental results is quoted as follows;

Sled Velocity Change	$\pm 1\%$
Sled Deceleration	$\pm 5\%$
Dummy Decelerations	$\pm 5\%$
Belt Loads	$\pm 5\%$
Excursions and Movements <sup>#</sup>	$\pm 4 \text{ mm}$

# Quoted for measurements from High Speed Video (Worst Case)

### 5.2 CRASH VICTIM SIMULATION OF FRAMED CHILD SEATS USING MADYMO

The crash victim simulation which was conducted in this project utilised a software package designed for this purpose. This package is called MADYMO (MAThematical DYnamic Model). A brief introduction to this package is included as section 2.3.1. For further details of the software package, reference should be made to the MADYMO manuals and Prasad (1985). The production of the first validated model, together with learning the MADYMO package, was carried out over a period of five months.

This portion of the thesis documents the use of MADYMO in this particular application. The next section discusses the construction of the model, there then follows a description of the validation process used to assess the model's fidelity to the actual test.

The particular details and problems of running MADYMO on the Middlesex University Vax system are discussed in Appendix E.

#### 5.2.1 MODEL CONSTRUCTION

The complete listing of the verified model [SIMLG2] is included in Appendix B. The model comprises three systems;

- (1) The Adult Test Seat - Inertial System.
- (2) The Occupant - System 1.
- (3) The Child Restraint - System 2.

The adult test seat in the simulation, is fixed in space. The sled deceleration is applied positively to the occupant and CR, rather than negatively to the adult test seat. This method representing sled deceleration is common amongst mathematical models and yields the same result as a deceleration applied to the sled. The only point that must be remembered, is that the sled deceleration pulse must be subtracted from the MADYMO output decelerations. The occupant acceleration output by MADYMO will be the response plus the input. Thus we must subtract the input to leave the response acceleration.

The deceleration pulse applied in the simulations, was that measured in a typical ECE R44 test conducted at RSEL (test T1922). This was considered a typical pulse shape and this test was used to validate the model. The interaction between the three systems is defined by belt systems and contact interactions between elements. Figure 5.4 shows the model SIMLG2 in the initial pre-impact position. The model that was created for use in this project will now be discussed in the following appropriate sections.

#### 5.2.1.1 THE ADULT TEST SEAT

The model of the adult test seat (inertial system) was constructed from five planes. Three to define the seat cushions. One to define the rigid seat pan and one to define the rigid seat front (see Appendix B, Figure B.1). All dimensions were taken from the ECE R44 standard and the actual test seat. The section of the input code which describes the adult test seat follows;

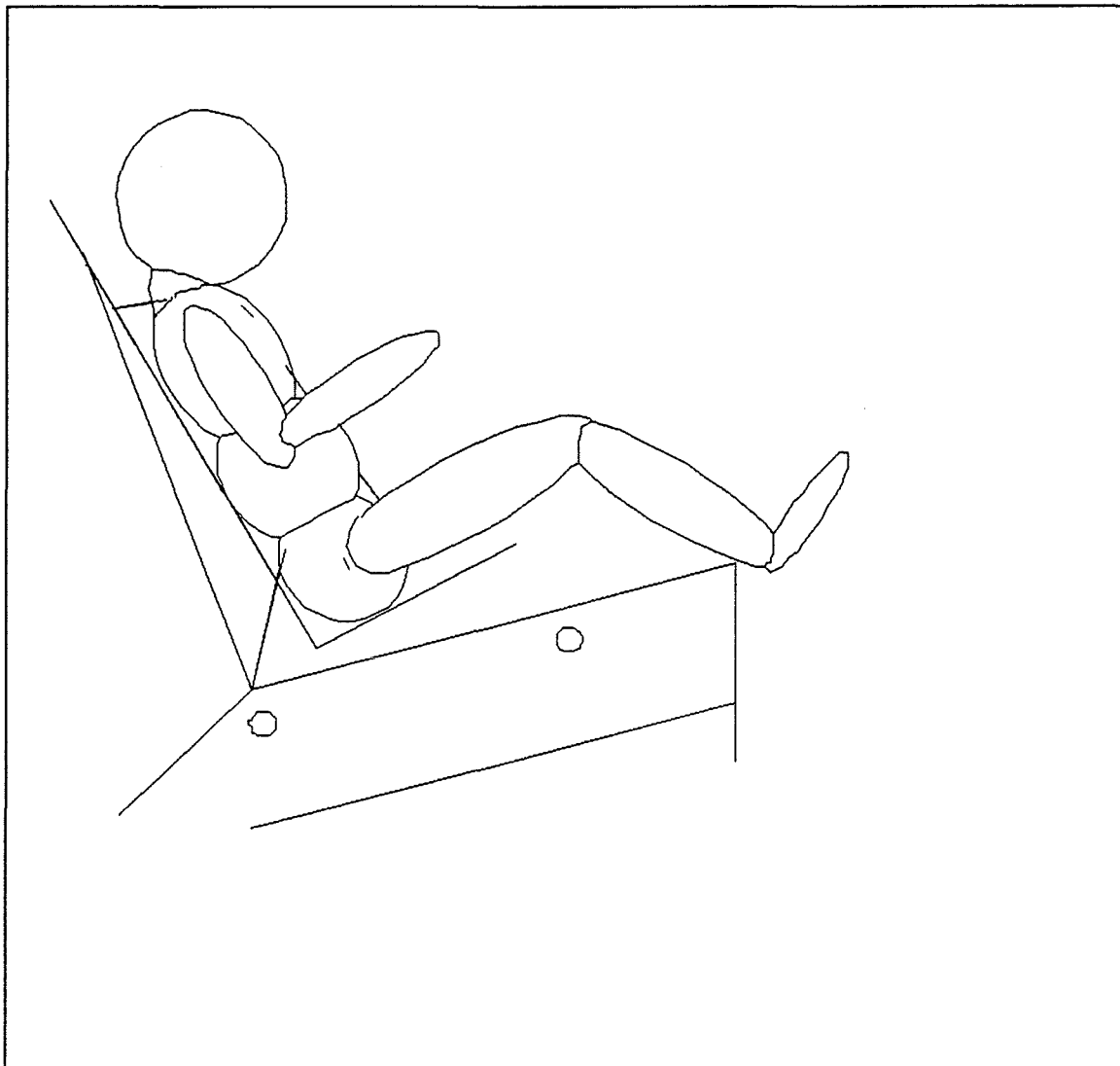


Figure 5.4. Side elevation of CVS SIMLG.

INERTIAL SPACE

ECE R44 SEAT

PLANES

0	0.0	-0.400	0.000	0.460	-0.400	0.125	0.460	0.400	0.125	1	0	0
SEATSQUAB												
0	0.0	-0.400	-0.140	0.460	-0.400	-0.015	0.460	0.400	-0.015	3	0	0
SEATWELL												
0	0.0	-0.400	0.000	0.000	0.400	0.000	-0.160	0.400	0.435	2	0	0
SEATBACK												
0	0.460	0.400	-0.015	0.460	-0.400	-0.015	0.460	-0.400	-0.075	3	0	0
SEATFRONT												
0	0.460	0.400	0.125	0.460	-0.400	0.125	0.460	-0.400	-0.015	4	0	0
SEATFRSQ												

-999

FUNCTIONS

8

0.0 0.0 0.027 36 0.056 145 0.107 535 0.114 635 0.120 750 0.135 1200 0.139 1600

3

0.0 0.0 0.100 2100 0.11 10000

2

0.0 0.0 0.001 10000

2

0.0 0.0 0.09 1000

The planes are defined via three of the corners, plus the reference number of the function block which defines its' force-deflection characteristics. The force deflection characteristic for the squab (first two lines of function block) is dependent upon the number and type of CR feet. As shown it represents the characteristic for one bar foot. The characteristic was measured by applying a static load on the CR foot and measuring the induced displacement (See Appendix C).

#### 5.2.1.2 THE OCCUPANT

The occupant model (system 1) was already available. A validated database of the TNO P3 dummy is supplied with the MADYMO 3D software. For use in the bulk of the simulation work, all that was required was to position the occupant within the CR model. This was achieved simply by a single position coordinate, for the root element of the model [lower torso], followed by a series of orientation commands to rotate the other elements [spine, upper torso, head etc] into a reasonable seated position. The occupant model listing can be found within the full CVS listing in Appendix B.

The occupant model was altered for the later stages of the simulations, by the addition of an improved neck model. This work is discussed in Chapter 11.

#### 5.2.1.3 THE CHILD RESTRAINT

The CR model (system 2) was based on measurements taken directly from the surrogate FCS. The CR is represented as configured with the shell in position "g" and standard bar foot. The CR model is

composed of a single rigid element, with four contact surfaces; two ellipsoids (feet) and two planes (shell back and base) (see Appendix B, Figure B.2 for coordinate positions). The MADYMO input data which represented the child restraint was as follows;

```

SYSTEM 2
CHILD RESTRAINT
CONFIGURATION
1
-999
GEOMETRY
0.0 0.0 0.0 0.082 0.0 0.244 CRMASS
-999
INERTIA
7.5 0.2 0.23 0.2
-999
ORIENTATIONS
1 1 1 2 0.07
-999
ELLIPSOIDS
1 0.0125 0.200 0.0125 0.000 0.000 0.000 20 0 0 0 REAR BAR
1 0.0125 0.200 0.0125 0.304 0.000 0.000 20 0 0 0 FRONT BAR
-999
PLANES
1 0.069 -0.140 0.059 0.280 -0.140 0.106 0.280 0.140 0.106 +
1 2 2000000 CRSEAT
1 0.069 -0.140 0.059 0.069 0.140 0.059 -0.050 0.140 0.560 +
1 2 2000000 CRBACK
-999
FUNCTIONS
3
0.0 0.0 0.0013 31 0.0102 446
2
0.0 0.0 0.01 50
-999
* INITIAL POSITION OF CR LOWERED INTO SQUAB 50mm
INITIAL CONDITIONS
0.010 0.0 -0.0355
ORIENTATIONS
1 -1 1 2 -0.279
-999
END SYSTEM 2

```

Moments of inertia of the CR, about the three axis, were measured using the compound pendulum method (See Appendix C).

#### 5.2.1.4 BELT SYSTEMS

Belt systems are defined in MADYMO by their attachment position on the systems, and their load-deflection curves. All load deflection characteristics were measured statically using a

tensile test machine (see Appendix C).

The adult lap belt system is defined in four elements, two on each side. One element on each side lies between anchorage and Cr point, the next between Cr point and CR. This configuration of belt sections was defined to give a realistic simulation of the actual belt route. The input data was as shown below;

**BELTS**

```
-1 0 -0.125 -0.200 -0.125 -1 0 0.000 -0.200 0.000 1 2 1300000 0.04 +  
0.1 0.0 0.0 1 ADULTLAPINB  
-1 0 0.000 -0.200 0.000 2 1 0.067 -0.200 0.162 1 2 1300000 0.04 +  
0.1 0.0 0.20 1 ADULTCRINB  
2 1 0.067 0.200 0.162 -1 0 0.000 0.200 0.000 1 2 1300000 0.04 +  
0.1 0.0 0.20 1 ADULTCROUT  
-1 0 0.000 0.200 0.000 -1 0 -0.125 0.200 -0.125 1 2 1300000 0.04 +  
0.1 0.0 0.0 1 ADULTLAPPOU
```

-999

**FUNCTIONS**

4

0.0 0.0 0.02 3500 0.03 4500 0.105 9000

3

0.0 0.0 0.05 0.0 0.08 2000

-999

A separate belt system, comprised of one element was added at a later date to represent the diagonal belt in the 3 point CVS [SIML-DI].

The child harness is defined in two belt systems of three sections each. One section passes from shell top to occupant shoulder, the next from upper torso to lower torso and the last section passes from lower torso to lower shell anchorage. Simulation of a crotch strap was not considered necessary. A crotch strap is not designed to be loaded, but merely hold the lap strap on the occupants hips. Movement of belts across the body is not simulated by this MADYMO belt subroutine, therefore a crotch strap is not required to locate the harness on the occupants' hips. The harness representation was as follows;

**BELTS**



```

2 1 -0.022 -0.060 0.438 1 3 0.000 -0.047 0.154 1 2 505100 0.04 +
    0.0 -0.31 0.033 0.2 CRTORLEF
1 3 0.059 -0.047 0.114 1 1 0.075 0.000 -0.070 1 2 900000 0.04 +
    0.1 0.0 0.06 0.2 CRMIDLEF
1 1 0.015 -0.075 -0.070 2 1 0.121 -0.139 0.125 1 2 1783000 0.04 +
    0.1 0.0 0.0 0.2 CRLAPLEF
-999
FUNCTIONS
2
0.0 0.0 0.15 8000
3
0.0 0.0 0.015 0.0 0.025 400
-999

```

Belt stiffnesses were measured statically. This component of the model includes the only estimated parameter. That is the belt correction factor 0.2, which corrects the belt force to allow for distortion of the shell anchorages and dummy body. This factor was estimated and then altered to yield the best result.

#### 5.2.1.5 CONTACT INTERACTIONS

Contact interactions can be defined in MADYMO for contacts between planes and ellipsoids and ellipsoids and ellipsoids. For the bulk of the simulations that were carried out in this project there was no need for any ellipsoid-ellipsoid contact interactions. Indeed these were ignored in the case of the head (or chin) to chest contact and head to leg contact. This was because it was not thought advisable to assess the performance of a particular child restraint configuration from accelerations induced by these contacts. ie; dummy and dummy database, biofidelity. Thus the following were the contact interactions specified for this model;

```

* INITIAL CONTACT FORCE IGNORED (COR=1).
CONTACT INTERACTIONS
PLANE-ELLIPSE
* SEAT-CR
-1 1 2 1 2 0 0 0 0 0 0.85 0.01 1 0
-1 1 2 2 2 0 0 0 0 0 0.85 0.01 1 0
-1 2 2 1 2 0 0 0 0 0 0.95 0.01 0 0
-1 2 2 2 2 0 0 0 0 0 0.95 0.01 0 0
-1 3 2 1 2 0 0 0 0 0 0.3 0.01 1 0

```

```

* SEAT-DUMMY
-1 1 1 12 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 13 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 15 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 16 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 11 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 14 2 0 0 0 0 0 0.3 0.01 0 0
-1 5 1 12 2 0 0 0 0 0 0.3 0.01 0 0
-1 5 1 15 2 0 0 0 0 0 0.3 0.01 0 0
* CR-DUMMY
 2 1 1 1 2 0 0 0 0 0 0.5 0.01 1 0
 2 1 1 11 2 0 0 0 0 0 0.5 0.01 0 0
 2 1 1 14 2 0 0 0 0 0 0.5 0.01 0 0
 2 2 1 1 2 0 0 0 0 0 0.3 0.01 0 0
 2 2 1 2 2 0 0 0 0 0 0.3 0.01 0 0
 2 2 1 3 2 0 0 0 0 0 0.3 0.01 0 0
-999

```

#### END CONTACT INTERACTIONS

Each line of the code refers to the interaction of a particular element of a particular system and the plane into which it is penetrating. The force penetration data that is used for these contacts is that found with the plane listing.

#### 5.2.2 MODEL VALIDATION

No exact theoretical solution of this dynamic model is possible. Therefore validation of the CVS was completed by direct comparison with experimental results. The lap belt restrained simulation SIMLG was compared with the appropriate tests, numbers T1922 and T2198 (T1944 and T2282 for 3 point restrained CVS SIML-DI). Head and chest acceleration traces were compared, together with belt forces and the loci of head target movement. These comparison plots can be viewed in this document as Appendix D.

It can be seen that the test and CVS traces are generally of similar shape and magnitude. However there are some differences. The most noticeable differences are the head x component acceleration, and the 3 point diagonal belt load. The former was considered to be due to a lack of a head-chin contact and the simple neck model in the P3 dummy database. However, this test-

model deviation was not considered a serious problem, given that the neck of the P3 dummy is not generally considered totally representative of the human neck and thus head response is generally not considered as an injury criterion.

The difference between the CVS and test diagonal belt loads remains unexplained, as the model was based on the actual belt characteristics. However, since the occupant acceleration data from the model compared well with the test, no attempt to improve the belt load response was made.

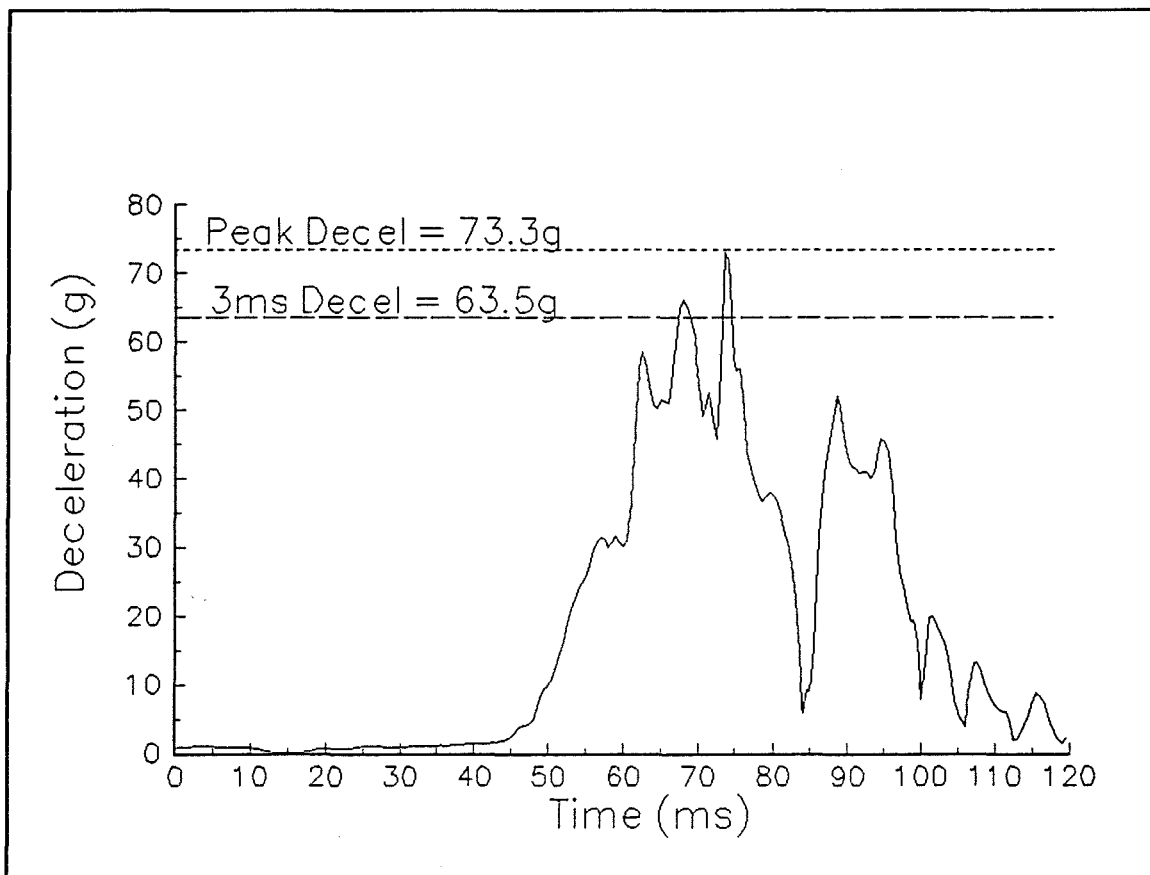
### 5.3 METHOD FOR ASSESSMENT OF CHILD RESTRAINT PERFORMANCE

The method for assessing the performance of a particular child restraint configuration was similar for both the crash test and simulation results. The philosophy for improving the child restraint performance was to reduce various Injury Potential Indicators (IPIs). These IPIs were selected firstly, on the basis of what could be measured during a test, secondly by what was considered a reliable dummy response and thirdly for estimation of potential for a particular injury mechanism.

The TNO P3 dummy that was used in these tests could be instrumented with two triaxial accelerometers, one in the upper torso and one in the head. The three orthogonal traces from these accelerometers could be studied individually or a single resultant acceleration could be calculated. In order to reduce the complexity of the performance assessment, the resultant acceleration was used. The biofidelity of the head and neck of the TNO P3 dummy is somewhat in question, therefore for the most part the head acceleration was not used as an IPI. Measurement of this data was conducted, and examination made to check for any

major variations.

The TNO P3 dummy is much more rigid than a human body, and therefore the dynamic response rate is higher. Acceleration traces exhibit many high spikes, due to the high response rate and impacts of body segments on other segments and external objects. These spikes are generally considered to be damped out by a human body subjected to similar loadings. Thus the high peaks that are seen in the dummy response are generally ignored and the so called 3 millisecond (3ms) value taken.

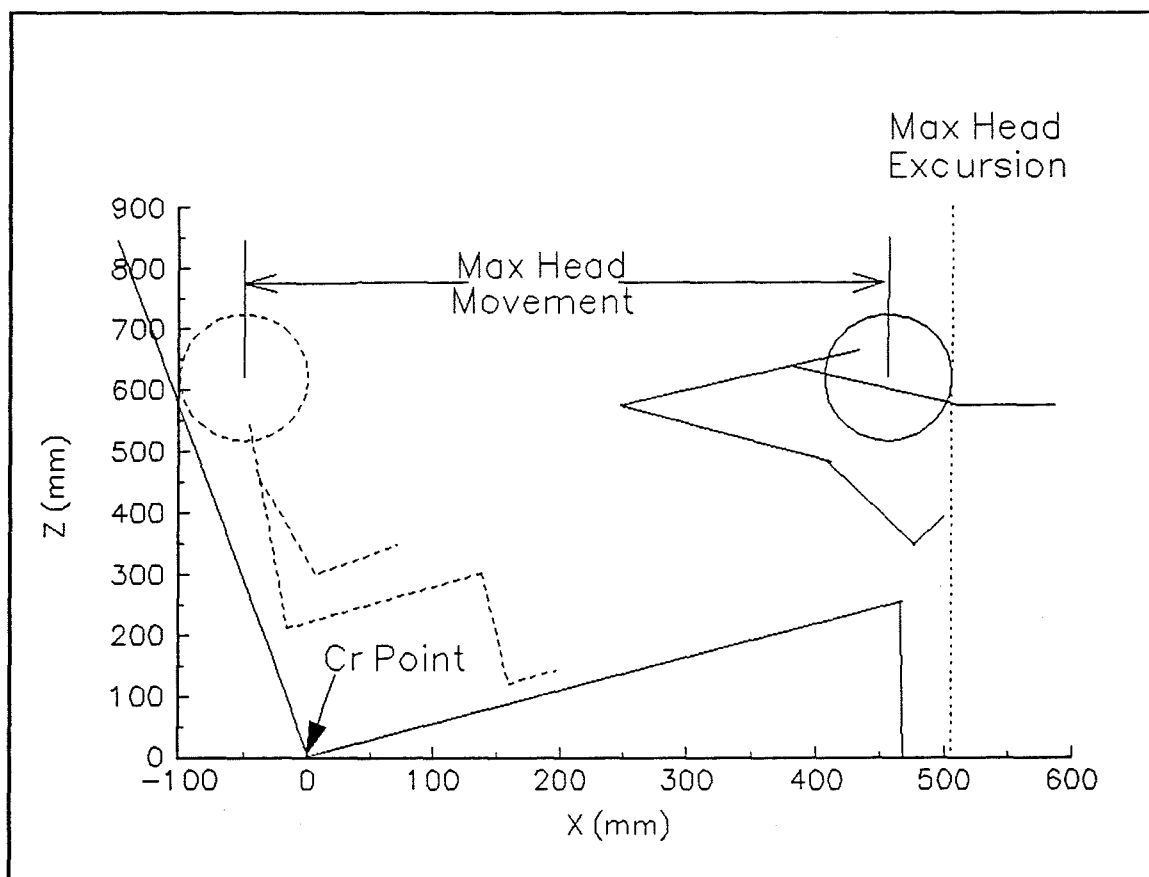


**Figure 5.5** The 3 millisecond value taken off a deceleration response of a TNO P3 dummy.

Figure 5.5 shows a typical chest resultant deceleration curve as measured in a TNO P3 dummy test. The peak value of chest deceleration is shown to be 73.3g. The 3ms value is, by definition, lower at 63.5g. The 3ms value is calculated by

ignoring deceleration peaks of total summed width 3ms. That is, move a horizontal line down the deceleration curve until all the peaks which cross it, occur in a total time of 3ms. This value is taken as the deceleration which would be seen by a human body. The 3ms deceleration is generally applied to the upper torso acceleration, but it can be applied arbitrarily to any acceleration curve.

The Chest resultant 3ms deceleration is one of two IPIs used to assess the child restraint performance during experimental testing. The second IPI that was used was concerned with reducing the possibility of head contact with some part of the vehicle. In order to reduce this probability, the movement or excursion of the head must be reduced. This Head movement was the second IPI.



**Figure 5.6** Measurement of Head Excursion and Movement from High Speed Film or Video recording.

The measurement of head excursion and head movement were conducted by analysis of the high speed film or video recording. Both film and video analyzers have the ability to output scaled position coordinates for any point in the picture. For the purposes of head excursion, the output is scaled in millimetres with a position origin at the seat Cr point (see Figure 5.6). The seat Cr point is the juncture of the two surface planes of the ECE R44 adult test seat. The head excursion is the maximum horizontal position of any point on the dummy head during the test and is measured from the Cr point. ECE R44 imposes a 550 mm limit on this value, but there is some concern that this is too high 4.1.2.

For this project it was necessary to define a second parameter for evaluating the head movement of the occupant. This second parameter was necessary to take into account the variations in head initial position that occurred with different child restraint configurations. This parameter was defined as the horizontal movement of the target on the side of the dummies head, relative to the head initial position. This measurement is also shown in Figure 5.6.

The use of the MADYMO crash victim simulation allowed the consideration of other injury potential indicators, that were not possible during the test programme. The most important of these factors was the neck load and the head angular acceleration. These parameters were considered not as absolute values for injury assessment, due to the lack of confidence in the dummy biofidelity. But it was considered appropriate to accept a reduction in these parameters as a reduction in the potential for injury.

Thus the Injury Potential Indicators (IPI) used to assess the performance of the child restraints in this project are as follows;

- Maximum Head Excursion
- Maximum Head Movement
- 3ms Resultant Chest Deceleration
- Neck Axial Load
- Head Angular Acceleration\*

\* Used in CVS study only.

The biofidelity of the dummy used in this project is such that none of these parameters could be considered accurate values which are representative of a true child response. The philosophy of the work conducted in this project was to reduce these values as much as possible. It is reasonable to accept that this will be likely to reduce the injury levels of a child subjected to the same crash situation.

## 6 PROGRAMME OF STUDY



## 6 PROGRAMME OF STUDY

The last chapter discussed the methodology used in the experimental and computer simulation work. And the previous chapters have provided background information on child car seats and crash simulation. This chapter comprises an introduction and guide to the results of the work that has been conducted during this research programme. The work that was conducted in this project falls into three main areas;

- 1) Investigation of child restraint design parameters on the performance of the framed child seat.
- 2) Investigation of vehicle parameters on the performance of the framed child seat.
- 3) Investigation of some occupant and child restraint parameters on the potential of injury to the occupant's head and neck.

Details of the programme of study relevant to these three areas are discussed in the following three sections. The fourth section provides a guide to the organisation of the results.

### 6.1 INVESTIGATION OF CHILD RESTRAINT DESIGN PARAMETERS ON THE PERFORMANCE OF THE FRAMED CHILD SEAT

This was the first part of the investigation and was initiated using experimental crash testing. Preliminary tests were conducted using a production framed child seat (FCS) to examine the effect of a variation in adult belt route. However, it was quickly realised that the production FCS was not suitable for this type of testing. Excessive frame deformation occurred when the production FCS was not used as defined in the manufacturers instructions. Thus the surrogate test seat, which is described in section 5.1.2, was used for the remainder of the test programme.

The test programme examined the effect of a variation in the following factors;

- 1) Adult belt route on a typical production child restraint
- 2) System centre of gravity via a change in seat shell position.
- 3) FCS foot size
- 4) Seat shell inclination
- 5) Effect of a top tether
- 6) Adult belt route on the surrogate FCS

Once the test programme was completed, much of this work was then repeated and extended with the MADYMO Crash Victim Simulation (CVS) model. This allowed verification of the results and additional validation of the model. The MADYMO model was also able to simulate a test configuration more rapidly and at a lower cost than a test. Therefore when repeating the test work it was possible to simulate a greater number of configurations. The results of a computer simulation are also not subject to erratic experimental errors. Thus the use of a computer model produced a greater understanding of the dynamic processes involved in child occupant restraint.

The computer model also allowed the investigation of parameters that were not easily studied with experimental techniques. Additional parameters that were examined using the CVS technique were;

- 1) Pure FCS Centre of Gravity movement
- 2) Mass of FCS
- 3) Mass Moment of Inertia of FCS
- 4) Webbing Stiffness
- 5) Shell Stiffness

## 6) Harness Slack

### 6.2 INVESTIGATION OF VEHICLE PARAMETERS ON THE DYNAMIC PERFORMANCE OF THE FRAMED CHILD SEAT.

The dynamic performance of a framed child seat (FCS) must be dependent upon not only the actual restraint design, but also the vehicle in which it is fitted. The FCS relies on the seat squab and pan for some anchorage as well as the standard adult seat belt. Thus variations in the vehicle geometry or squab material parameters are likely to affect the performance of the restraint.

This section of the project was mostly conducted using the MADYMO model. It was simpler, more cost effective and less time consuming to use the model rather than a full crash test. Some tests were conducted with production model car bodies bolted onto the sled, however, it was impossible to identify the reason for any change in FCS performance. This was because several parameters can vary in any single vehicle from the ECE R44 test seat design. Identifying which parameter is the critical factor which alters the dynamic performance was therefore not possible unless a special test seat was constructed.

The vehicle parameters that were examined were as follows;

- 1) Seat Squab Stiffness
- 2) Seat Squab Depth
- 3) Adult Belt Anchorage Positions
- 4) Vehicle Deceleration Pulse
- 5) Adult Belt Slack

These features were chosen as factors which were likely to vary between different vehicles and likely to affect child restraint performance.

### 6.3 INVESTIGATION OF SOME OCCUPANT AND CHILD RESTRAINT PARAMETERS ON THE POTENTIAL OF INJURY TO THE OCCUPANT'S HEAD AND NECK.

This section of the project is distinct from the rest of the project in that it required a modification to the standard MADYMO dummy database which is supplied by TNO. Up to this point in the project no real assessment had been made of the possibility of reducing non contact head and neck injuries. It was felt that the neck fidelity of the MADYMO database to the dummy was not good enough to investigate this area. Thus an improved neck model was created for use in the latter stages of the project.

The parameters which were examined in this section of the project were;

- 1) Chin-Chest Contact Stiffness
- 2) Child Head Mass
- 3) Inclination of Occupant Seat
- 4) Position of Centre of Rotation of Head Movement

### 6.4 PRESENTATION OF RESULTS

The results of the test and simulation programme are discussed in the next few chapters. For convenience the results are discussed in chapters which separate the three areas of study and the two methods of investigation (see Figure 1.6).

The chapters are arranged in roughly the chronological order in which the work was conducted. Firstly the experimental investigation into child restraint design parameters is presented in Chapter 7. Following that the computer simulation study of the same subject are discussed in Chapter 8. Chapter 9 documents the experimental vehicle parameter investigation and Chapter 10 is

the computer simulation study of the same. Following that in Chapter 11 are the results of the modelling work which looked at specific non-contact head and neck injuries and Chapter 12 presents a limited study into child restraint misuse. The work is then drawn together in a discussion (Chapter 13) and conclusions are drawn in Chapter 14.

7 RESULTS OF AN EXPERIMENTAL STUDY  
OF THE EFFECT OF SOME CHILD  
RESTRAINT DESIGN PARAMETERS  
ON THE DYNAMIC PERFORMANCE

## 7 RESULTS OF AN EXPERIMENTAL STUDY OF THE EFFECT OF SOME CHILD RESTRAINT DESIGN PARAMETERS ON THE DYNAMIC PERFORMANCE

This part of the project was concerned with the study of the parameters of the child restraint which affect the dynamic performance of the restraint and the injury potential to the occupant. Many of the framed child seats (FCS) which are currently in production were originally designed so as to require the minimum in capital outlay. The minimisation was achieved by using existing parts from four point child restraints. In particular the shell seat is common to many manufacturer's four point and framed child seats. In addition many FCS were initially conceived as four or two point child seats. Thus FCS were not conceived as original designs, rather as an alteration to an existing design. In principle there is nothing wrong in using existing parts. The problem as perceived at the start of this project was that the optimum configuration for the restraints could have been sacrificed for reduced costs. In addition the child restraints were designed before the British standard was altered to encompass this new type of seat. The seats were initially tested using a method designed in the early 1960's (BS 3254:1960). There was some concern that the restraints in production were not optimised for modern vehicles and test conditions.

A test programme was designed to examine the appropriate parameters of framed child seats and to optimise the design configuration. The test methods and results will be presented in order of test phase. Each phase of the work studied one particular design parameter which were as follows;

- 1) Variation of adult belt route on a typical production child restraint

- 2) Variation of system centre of gravity via a change in seat shell position.
- 3) Variation of FCS foot size
- 4) Variation in seat shell inclination
- 5) Effect of a top tether
- 6) Variation of the adult belt route on the surrogate FCS

All of the phases bar the first were conducted using the surrogate FCS described in Appendix A. After each phase the optimum configuration was assessed and this configuration was used in the next and subsequent phases. As will be seen this choice of optimum configuration was subjective, and could be assessed differently using alternative criteria. The tests discussed in this chapter were all conducted in a forward facing frontal impact mode as described in section 5.1.

This work was conducted mainly under contract with the Transport Research Laboratory (TRL) and for the most part has been documented in previous publications (Dorn & Roy (1990) and Dorn, Roy & Lowne (1991)).

#### 7.1 THE EFFECT OF A VARIATION OF ADULT BELT ROUTE ON A TYPICAL PRODUCTION FRAMED CHILD RESTRAINT

The mass and centre of gravity of a sample of production FCS were measured and compared. The Britax 2-Way child restraint was found to be a typical child restraint, representing the middle of the range of these parameters and therefore this child seat was chosen for this the first phase of the dynamic testing. An added feature of this child restraint is that it is designed to be restrained with adult lap belts, 3 point belts or a fitting kit. As it was intended to test with the former two anchorage methods, this was an important consideration.



The variation in adult belt route comprised the movement of the lap section route over the seat frame. It was not possible to vary the diagonal section of the belt to any great extent, due to the restraint design. The diagonal belt in all current FCS designs passes through the frame behind the seating shell. It would not be reasonable to consider other, more complex, routes.

The lap belt section was varied over 7 different positions, including that which was recommended by the manufacturer. It was found during testing that all of the belt routes, other than that specified in the instructions, caused the child restraint to be loaded in a manner for which it was not designed, and therefore significant deformations of the frame were induced. It was therefore not considered appropriate to discuss the test results in any further detail. However, these results do have an interest in terms of misuse of child restraints, and it is recommended that further tests are conducted to identify potentially dangerous misuse modes which could lead to ejection of the FCS from the belt or excessive movement.

In the light of these test results it was considered inappropriate to use production child restraints in further phases of the project. The design of a surrogate FCS which could withstand the required variations in test configurations was therefore necessary. The design of the surrogate is discussed in section 5.1.2 and Appendix A. The next phase of the project utilised this surrogate seat in an examination of the effect of a variation in the centre of gravity of a framed child seat.

## 7.2 THE EFFECT OF A VARIATION IN OCCUPANT CENTRE OF GRAVITY

The first design parameter which was examined using the surrogate framed child seat (SFCS) was the importance of the location of occupant centre of gravity in the performance of a FCS. The surrogate FCS was designed to allow the variation of the position of the seating shell within the seat frame. Thus it was possible to vary the occupant centre of gravity within the child restraint system and then test the system performance. The variation in the position of the shell relative to the frame in British FCS is not great. On the whole the shell is low in the frame and is close to the rear. However, in some US and other FCS this is not always the case. For example the US Strolee Wee Care child seat has a seating shell approximately 100 mm above the FCS base (the Britax 2-Way seat shell is about 50 mm above the seat base). A higher seating position is generally considered preferable for the occupant as it allows a better view out of car windows. This phase of testing was designed to discover whether the mass centre location plays a major part in the system performance.

The shell position was varied by series of location holes drilled in the side plates (see Figure 7.1). These holes allowed the four shell support bolts to be fixed to the side plates in any one of nine positions. The central position (e) was the position of the shell in the "typical" production model. The other eight positions were located at 60 mm centres around this position.

As in most tests a standard 25 mm slack was induced in the internal SFCS harness and the SFCS was tested whilst restrained with both an adult surrogate lap belt and a 3 point belt.

With the FCS restrained with a surrogate lap belt, one test was

conducted for each of the nine shell positions as shown in Figure 7.1. This was not possible for the 3 point restrained case, as the 3 point belt routing obstructed the shell movement. Thus the FCS was only tested with the shell in the following six shell positions; a, b, c, e, f and i.

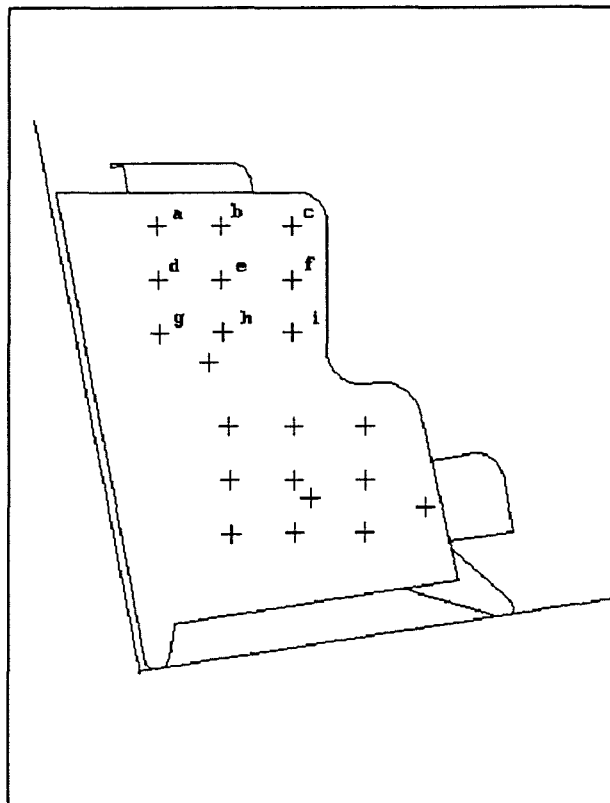


Figure 7.1 Positions of shell variation a - i

#### **7.2.1 RESULTS**

The visual performance of the various tests, as recorded on high speed film, was similar for all the tests. As expected the CRS restrained with a surrogate lap belt exhibited greater rotation than those restrained with a 3 point belt. The diagonal belt of the 3 point system provides an upper restraint which of course is absent in the lap belt restrained case. On the whole it was concluded that the variations in test results were due to geometric rather than inertial loading variations. Details of the results are discussed fully in the next two sections which separate the lap belt restrained case from the 3 point.

##### **7.2.1.1 THE LAP BELT RESTRAINED CASE**

The results of the tests of a lap belt restrained surrogate FCS are summarised in Figure 7.2 (chest 3ms acceleration and head movement are defined in section 5.3). It can be seen that there is a general trend for lower head movement as the shell was moved forward and down. The decrease in head movement was due to the

lowering of the head position towards the point of rotation of FCS. This reduced the radius of rotation and therefore the arc of head movement. The effect of a change in shell position on chest deceleration was less clear. No apparent pattern was evident from these results.

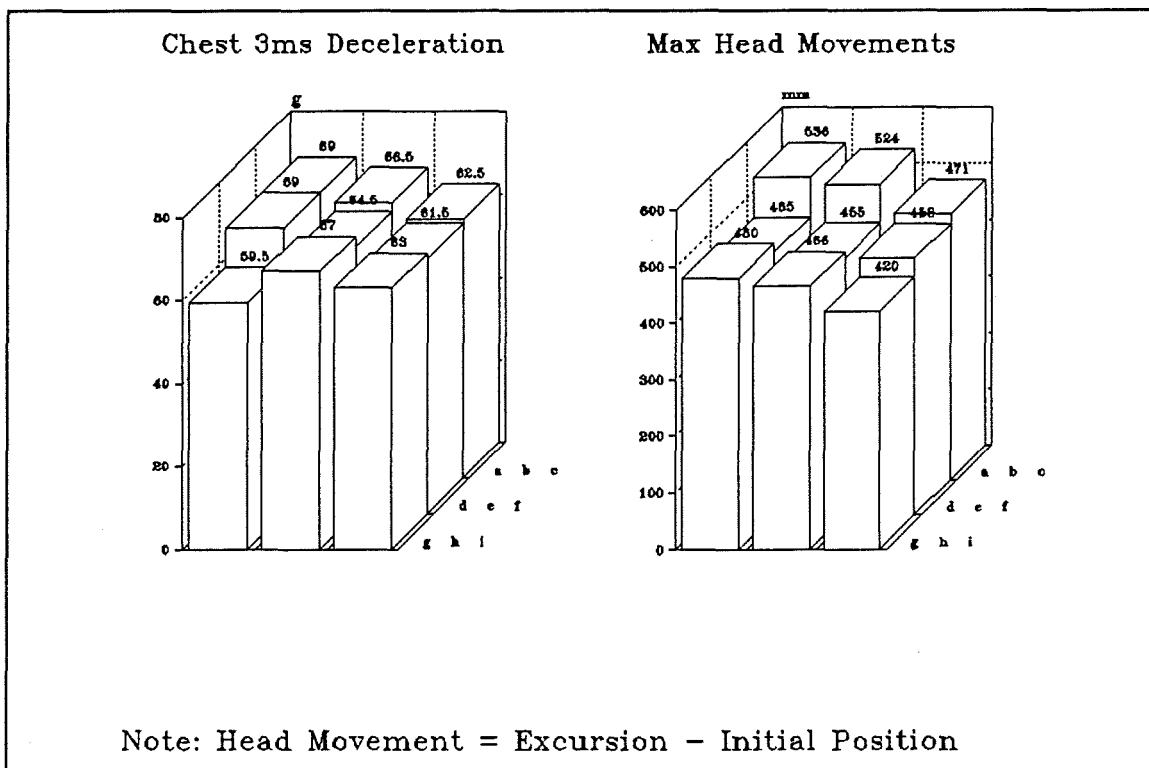


Figure 7.2 CG Pos. Lap belt restrained CR results.

The contract with TRRL under which this work was conducted required the selection of an optimum configuration to be used in the further sections of the contract. The concept was to gradually develop an optimised framed child restraint. The optimum chosen from these results was position "g". Although the head movement decreased as the shell was moved forward, the head excursion increased. This was of course due to the more forward initial position of the head. Thus the optimum position in terms of head excursion was position "g". The test of the FCS with the shell in this position also exhibited the lowest chest 3 ms

deceleration, thus the choice of optimum position g was justified.

#### 7.2.1.2 THE 3 POINT RESTRAINED CASE

The 3 point restrained results exhibit similar trends to the lap belt restrained case. Both the chest deceleration and head movement were generally reduced as the shell position was moved forward and down (see Figure 7.3). Thus position "i" was chosen as the optimum configuration. The trends as discussed are not totally evident from the test results. In addition to this work MADYMO simulation was used in parallel and this showed the trends more clearly (see next chapter).

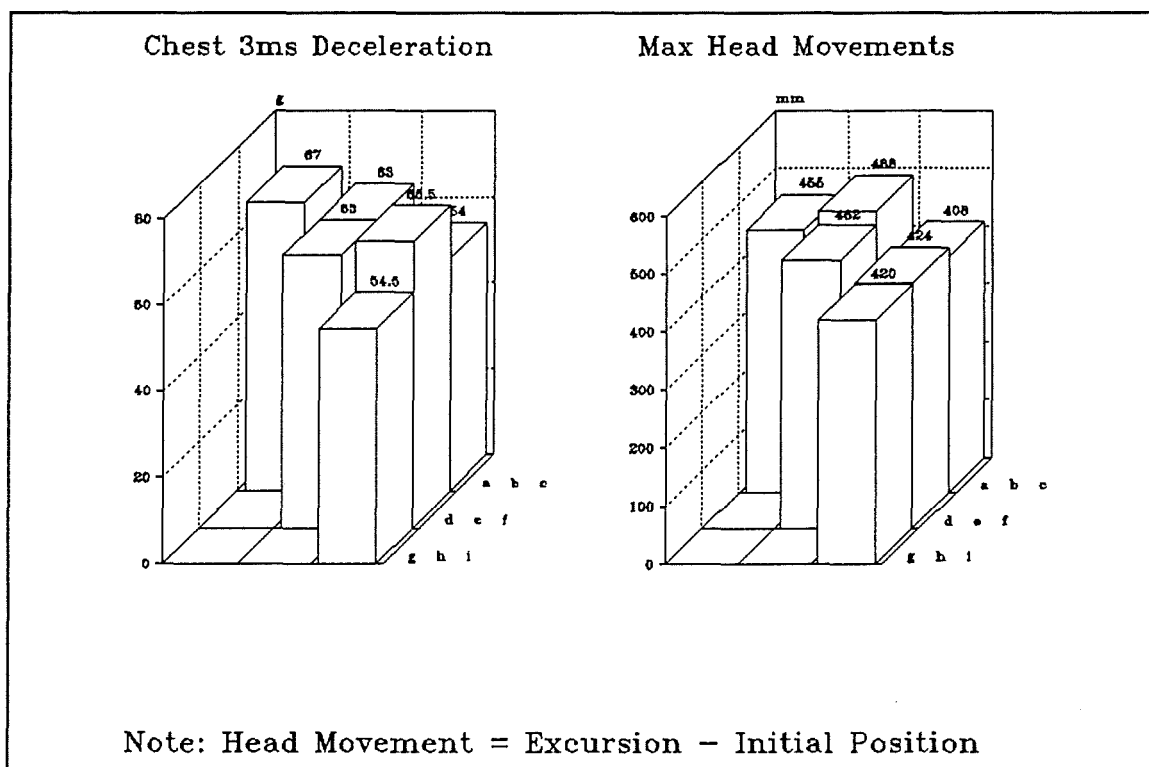


Figure 7.3. CG Pos. 3 point belt restrained CR results

It is thought that the results shown here were subject to experimental error and scatter which partially obstructs the true effect of the change in shell position. In addition the upper restraint which is supplied by the diagonal belt, reduces the effect of a change in shell position.

### 7.3 THE EFFECT OF CHILD RESTRAINT FOOTPRINT AREA

The framed child seat rests on the adult car seat and in impact tests can be seen to sink into the seat. The contact between the restraint and vehicle seat was therefore thought to perform a function in the deceleration of the occupant in a framed child seat. Thus it was considered important to investigate how changes in foot area, and thus magnitude and position of contact forces, would affect the dynamic response. Traditional child restraint foot design comprises two, approximately 25 mm diameter, steel tubes running laterally across at the base of the child restraint. It was not known how an increase in this minimal foot area could affect the performance of the child restraint.

The surrogate FCS as used in the previous part of the project was configured with a typical style bar foot at both front and rear of the restraint. In addition to this foot configuration four types of plate foot area were bolted on to the surrogate FCS. The dimensions and positions of these are summarised in Table 7.i.

**Table 7.i** The five foot sizes used in this investigation

Foot No.	Size (mm)	Position
1	25 dia x 400 Bar	Both Feet
2	50 x 400 Plate	Front Foot <sup>#</sup>
3	100 x 400 Plate	Front Foot <sup>#</sup>
4	320 x 410 Plate	Total Base
5	450 x 460 Plate	Total Base

# Rear foot was standard 25 mm dia bar

Tests were conducted with the surrogate FCS restrained with both a surrogate lap belt and a 3 point belt. The shell positions used were the optimum locations found in the last phase, that is;

position g for the lap belt restrained tests and position "i" for the 3 point restrained tests. It should be noted that the difference in shell positions for the two restraint cases means that the results can not be directly compared.

#### **7.3.1 RESULTS**

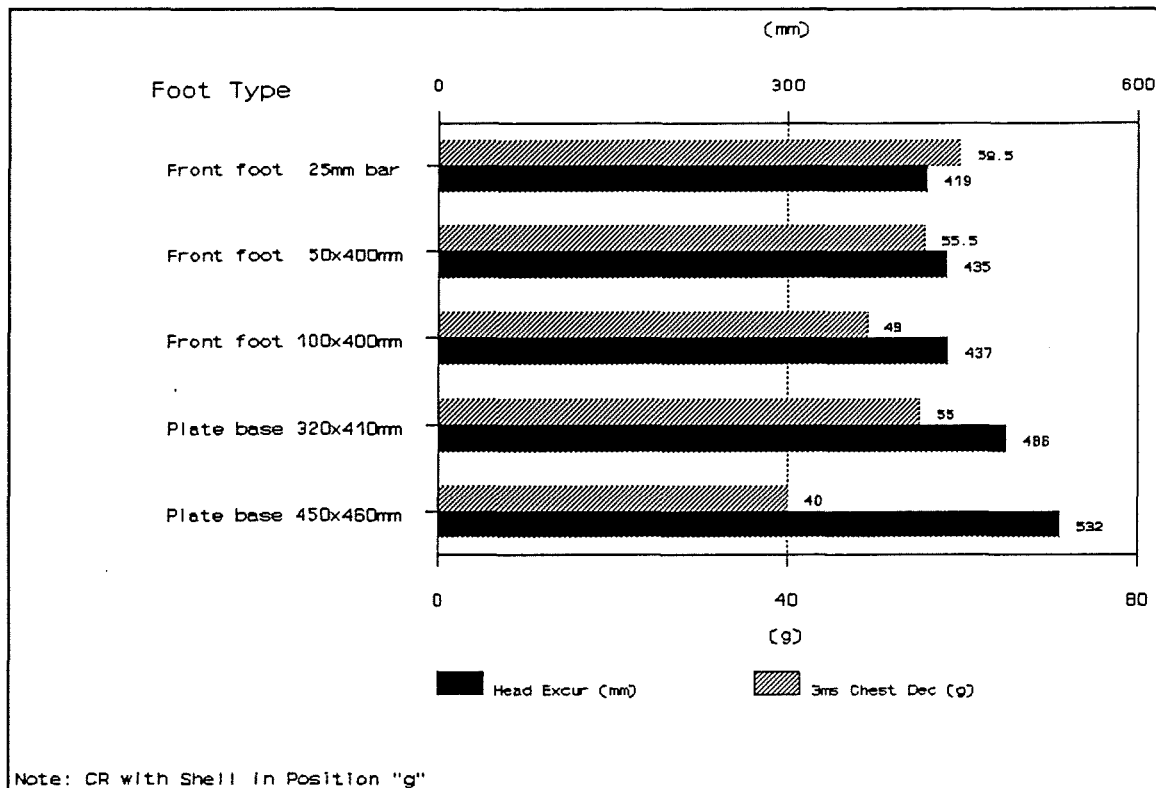
The results are presented in the following two sub-sections. Firstly for the lap belt restrained FCS and then the 3 point restrained case.

An important feature of these results is the difference in the effect of the foot size between the two FCS anchorage cases. As in the last section the addition of an upper restraint reduces the effect of FCS design parameter variation.

##### **7.3.1.1 THE LAP BELT RESTRAINED CASE**

The results of the variation in foot type tests of a surrogate FCS anchored with a surrogate adult lap belt are shown in Figure 7.4. There is an obvious pattern of increasing head excursion and decreasing chest acceleration as footprint area is made larger. Indeed the head excursion for the largest foot configured FCS is 27% higher, whereas the chest deceleration is 33% lower compared to the bar foot case. The choice of an optimum foot size is dependent upon the criterion used. In this case the large reduction in chest deceleration was considered to outweigh the increase in head excursion. The head excursion remained within the limits of the approval standards (550 mm ECE R44 / 600 mm BS3254 Part 2 : 1988) and therefore the largest foot was chosen as optimum.

The changes in surrogate FCS dynamic performance can be explained by an alteration in system stiffness, which was due to a



**Figure 7.4.** Foot size lap belt restrained results.

reduction in the initial compression (precompression) of the squab. When the bar foot surrogate FCS was placed on the ECE R44 test seat, the weight of the seat and dummy pushed the feet into the squab. This precompression was then accentuated, to a level of 50 mm, when the adult lap belt was tightened. When the same process was conducted with the largest plate foot configured FCS only a small ( $< 5$  mm) precompression was induced. The lack of precompression yields a greater depth of squab for the FCS to decelerate through before reaching the seat pan (the seat pan is the rigid cushion support which is often shaped with varying depth). In addition the horizontal force which the squab can exert is reduced. Precompression of the cushion also means that the length of webbing that is used in the adult lap belt, is reduced due to the FCS being closer to the anchorage. Therefore the reduction in precompression caused by the use of a larger foot, reduces system stiffness and therefore allows greater child restraint movement and lower accelerations.



### 7.3.1.2 THE 3 POINT RESTRAINED CASE

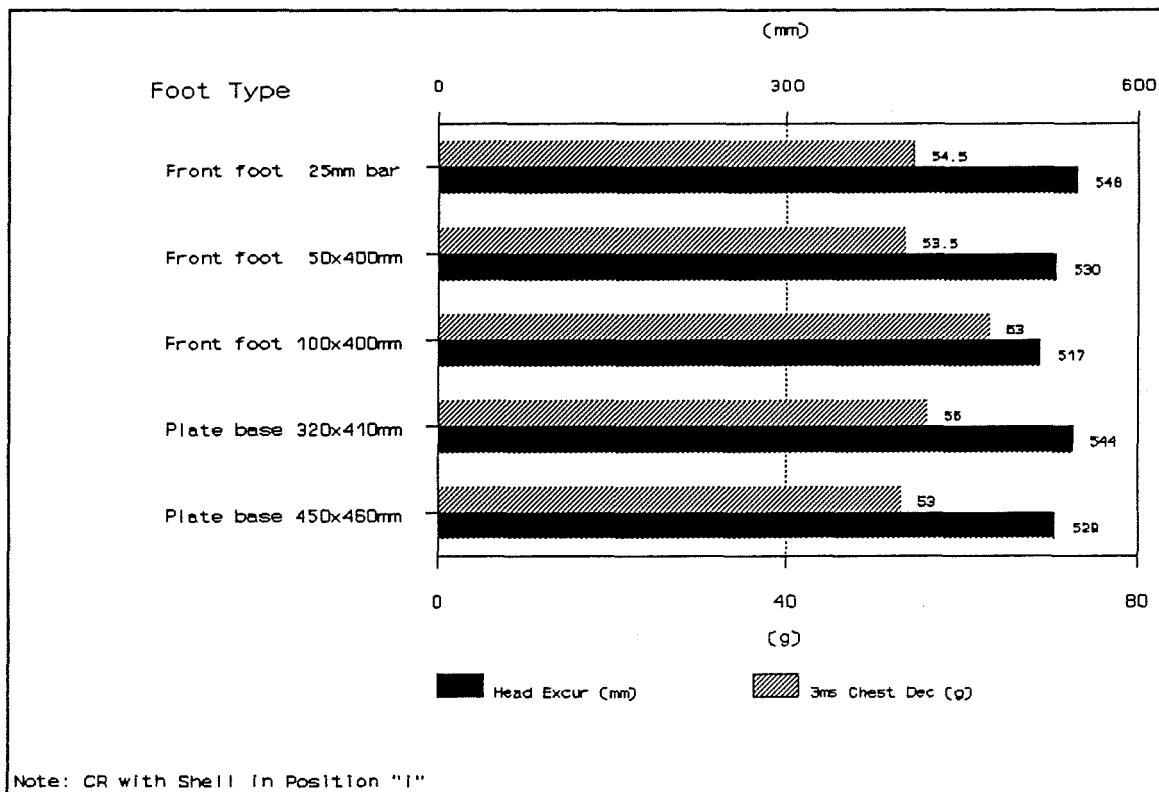


Figure 7.5. Foot Size 3 point restrained CR results

Figure 7.5 shows the results of the 3 point restrained surrogate FCS tests. The pattern of alteration in FCS dynamic performance was not evident in the 3 point results. Neither the chest acceleration or head excursion were apparently affected in any consistent manner by the alteration in foot size. It was therefore concluded that the main deceleration loads are those in the 3 point belt system and the squab contact plays a more minor role in the FCS restraint.

### 7.4 THE EFFECT OF SHELL INCLINATION

Many modern framed child seats include a shell reclining mechanism for added occupant comfort. This is particularly useful for the younger child, who may find an upright position uncomfortable on long journeys. When tested for an approval, the child restraint would generally be tested in both the fully

upright and fully reclined positions. However, quantification of how the shell inclination actually affects the occupant response and the potential for injury had not been achieved. Thus, a series of three extra tests were conducted to investigate the effect of a change in shell inclination on the dynamic performance of a FCS.

Four tests were planned for this phase, two with a reclined FCS restrained by an adult lap belt and two with a reclined FCS restrained by an adult 3 point belt. The intention was to test the surrogate FCS with the shell reclined about the top and then reclined about the bottom shell mount, for the two restraint cases. Unfortunately with the optimum shell position for a lap belt restrained FCS being low and back (shell position "g"), reclining about the base was not possible for this anchorage type. Therefore three tests were conducted as shown below;

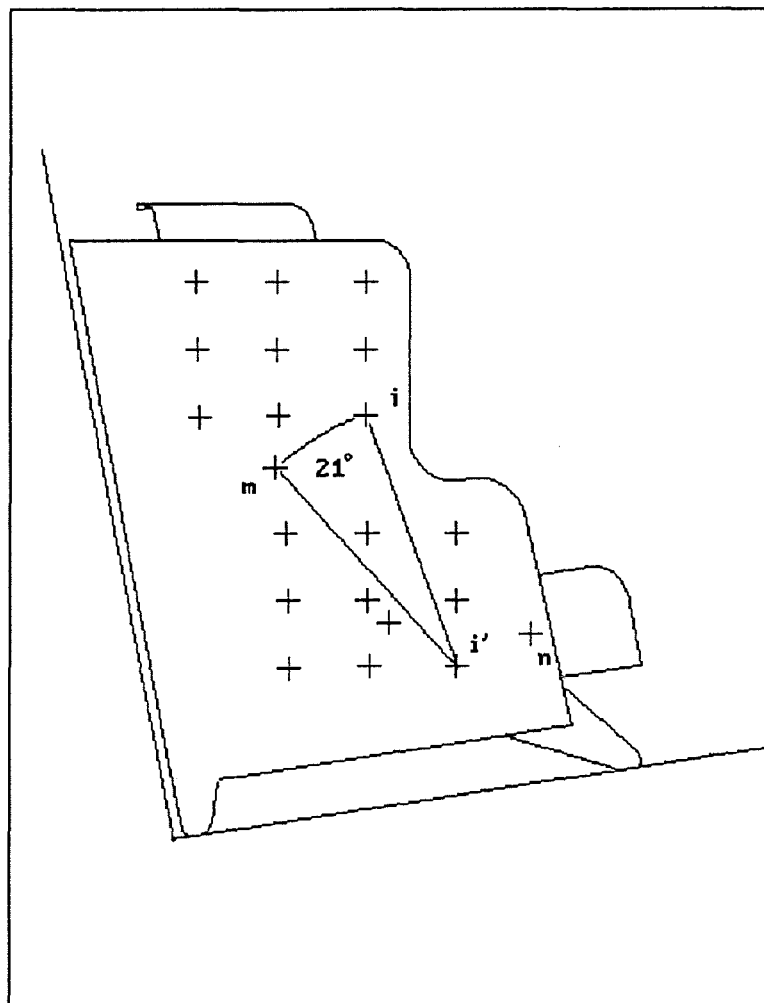
- Lap belt restrained FCS, shell reclined 21° about top
- 3 Point restrained FCS, shell reclined 21° about top
- 3 Point restrained FCS, shell reclined 21° about base

21° was chosen as the extra inclination in addition to the standard 5° amount. A small sample of reclining FCS exhibited angles of approximately this value.

The change in inclination of the surrogate FCS shell was effected by the addition of extra holes in the side plates (see Figure 7.6).

#### 7.4.1 RESULTS

It should be noted that there is a difference in surrogate FCS configuration between the two anchorage cases. The lap belt anchored test was conducted with the shell in position "g" and the largest footprint area. Whereas the 3 point restrained tests were conducted with the shell in position "i" and the standard bar



**Figure 7.6** The additional shell mounting holes for reclining

feet. These were the configurations as optimised in the previous test phases. Due to the differences in FCS configuration the results for the lap belt and 3 point restrained cases are not comparable.

##### 7.4.1.1 THE LAP BELT RESTRAINED CASE

The results of the test of a reclined shell, lap belt restrained surrogate FCS are shown in Figure 7.7 compared to the upright case. The results indicate a small increase in chest acceleration (10%) and a reduction in head excursion for the reclined FCS. Head excursion was reduced mainly due to the more rearward initial position of the head in the reclined configuration. Thus reclining of the seat shell was not seen to alter the restraint

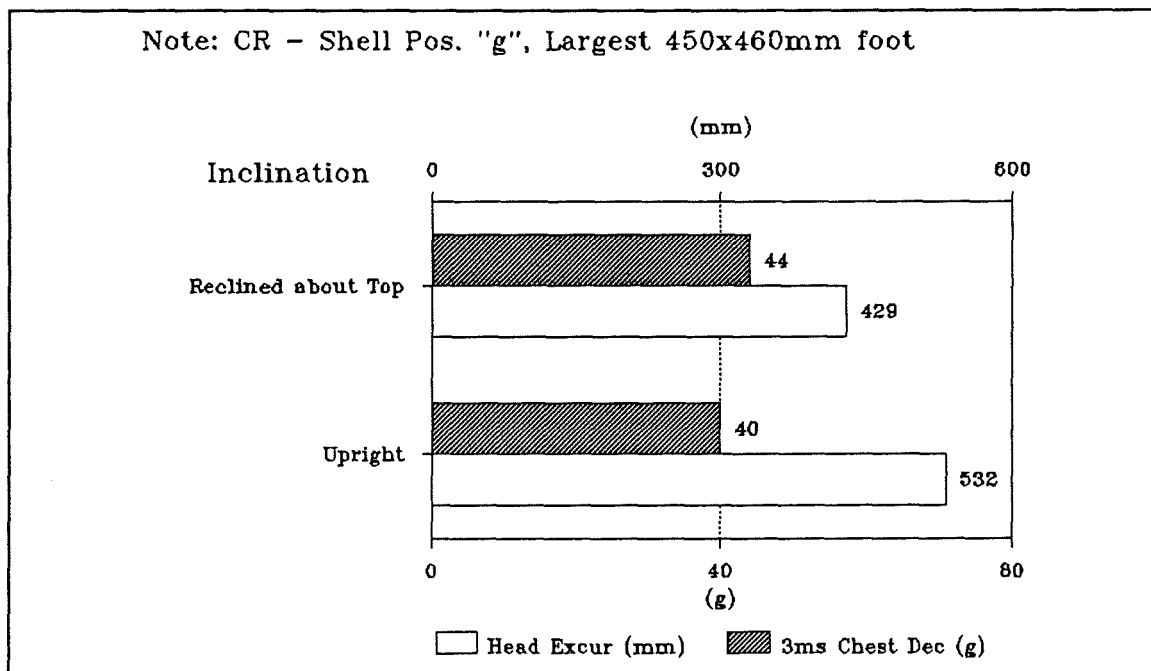


Figure 7.7. Shell inclination, lap belt restrained results

performance to any great extent when assessment was conducted using the standard procedures. However, it was also noted that the rebound acceleration (when the head hits shell) was greatly increased in the reclined test. It was not known whether this was a random occurrence or a feature of the reclined mode. It was conceivable that the angling of the seat shell implied a greater bending load in the occupant's neck as the head rotates forwards. This stored energy could then be transferred into a higher rebound velocity of the head. This theory could only be proven if the load in the dummy neck was measured. However no load cell for the TNO P3 dummy was available at the time of this project and therefore this theory could only be tested with the MADYMO crash victim simulation. This study is presented in Chapter 11.

#### 7.4.1.2 THE 3 POINT RESTRAINED CASE

Figure 7.8 shows the results of the two 3 point restrained, reclined tests compared again with the appropriate upright results. The results are similar to those observed in the lap

belt restrained case. Head excursions are decreased and chest accelerations increased. The greatest change in performance occurred with the shell reclined about the base shell mount. The head accelerations were again observed to be much greater for the reclined tests.

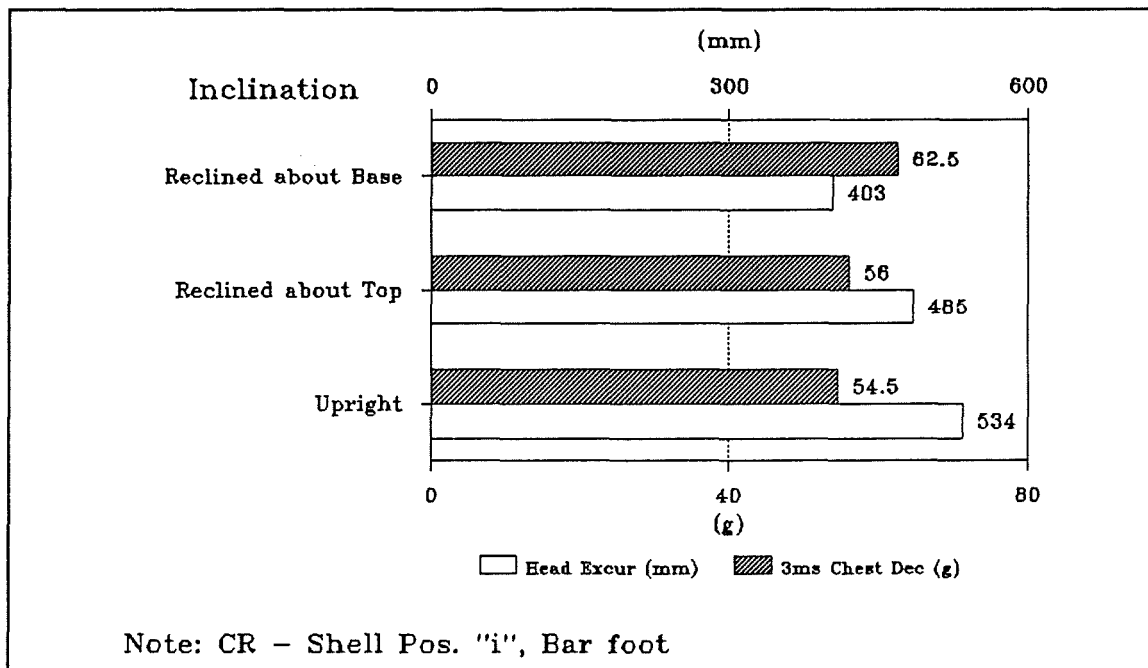


Figure 7.8. Shell inclination, 3 point restrained results

### 7.5 THE EFFECT OF TOP TETHERS

A top tether is an additional upper anchorage strap used to limit rotational movement of a framed child seat which is restrained by an adult lap belt. It generally comprises a length of 1" width webbing attached to the top of the framed child seat and the parcel shelf of a saloon car. Few British or European FCS's use this additional anchorage, but use is widespread in the United States of America and mandatory in Australia. With the advent of the hatchback and estate cars the top tether has become increasingly difficult to fit in Europe. The author knows of no current production FCS which utilises this anchorage method.

This phase of the research was designed to investigate the effect of the top tether on the dynamic performance of the surrogate FCS. To this end a series of tests was conducted with the surrogate FCS restrained with a lap belt and a surrogate top tether. The surrogate top tether comprised a double length of adult seat belt webbing which was wrapped around the upper rear shell support bar and anchored to a position on the sled which was considered a typical and correct anchorage position.

Tests were conducted with the surrogate FCS configured with both a bar foot and the largest footprint area.

#### 7.5.1 RESULTS

**Table 7.ii. Top tether results**

<u>Foot Type</u>	<u>Top Tether Used</u>	<u>Chest 3ms Deceleration</u>	<u>Max Head Excursion</u>
Bar	No	59.5	419
Bar	Yes	55.5	396
Largest Plate 450x460mm	No	40.0	532
Largest Plate 450x460mm	Yes	65.5	319

The results of the tests conducted with a top tether can be seen in Table 7.ii compared with the no top tether case. It can be seen that in the case of the surrogate FCS configured with a bar foot, the top tether had little effect. However, in the case of the largest plate foot surrogate FCS the top tether did reduce the head excursion by over 200 mm. The reason for the apparent dissimilarity in the effect of top tethers lies in the differences of the kinematics of the FCS configured with the two

foot sizes. We have already seen the effect of various footprint sizes on the dynamic performance of the surrogate FCS. That is, the larger foot size performance is typified by an increase in head excursion caused by an increase in FCS movement. And in the case of the bar foot configured surrogate FCS there is only limited child seat movement and thus little movement which the top tether can restrain. In the case of the plate foot surrogate FCS the movement is increased and the top tether therefore has a greater effect on performance.

The overall conclusion on the usefulness of top tethers is as follows;

- The effect of top tethers is dependent upon the child restraint design
- No large benefit of top tethers is evident from these results
- The reduction in head excursion observed in these tests was offset by an increase in chest acceleration

Top tethers which absorb energy could be one way of reducing head excursion whilst not increasing the chest deceleration. However, it is difficult to picture a device that would adsorb energy without extension and therefore such a device would not reduce head excursion to the levels observed in these tests.

#### **7.6 THE EFFECT OF ADULT BELT ROUTE ON THE SURROGATE FCS**

As discussed in section 7.1, it was not possible to determine the effect of different adult belt routes on the typical production FCS. Movement of the adult belt route induced incorrect loading of the child seat structure leading to local failures. It was therefore considered appropriate to examine this factor using the surrogate FCS. For this purpose extra holes were drilled into the

side plates of the surrogate FCS to provide a variety of attachment points for the adult belt surrogate (see Figure 7.9). In total five positions of lap belt were used for the tests conducted with a lap belt restrained FCS and a 3 point restrained FCS. For the 3 point restrained case only the lap belt position was varied. The surrogate FCS was configured with the standard bar foot and

standard shell position "e" for these tests.

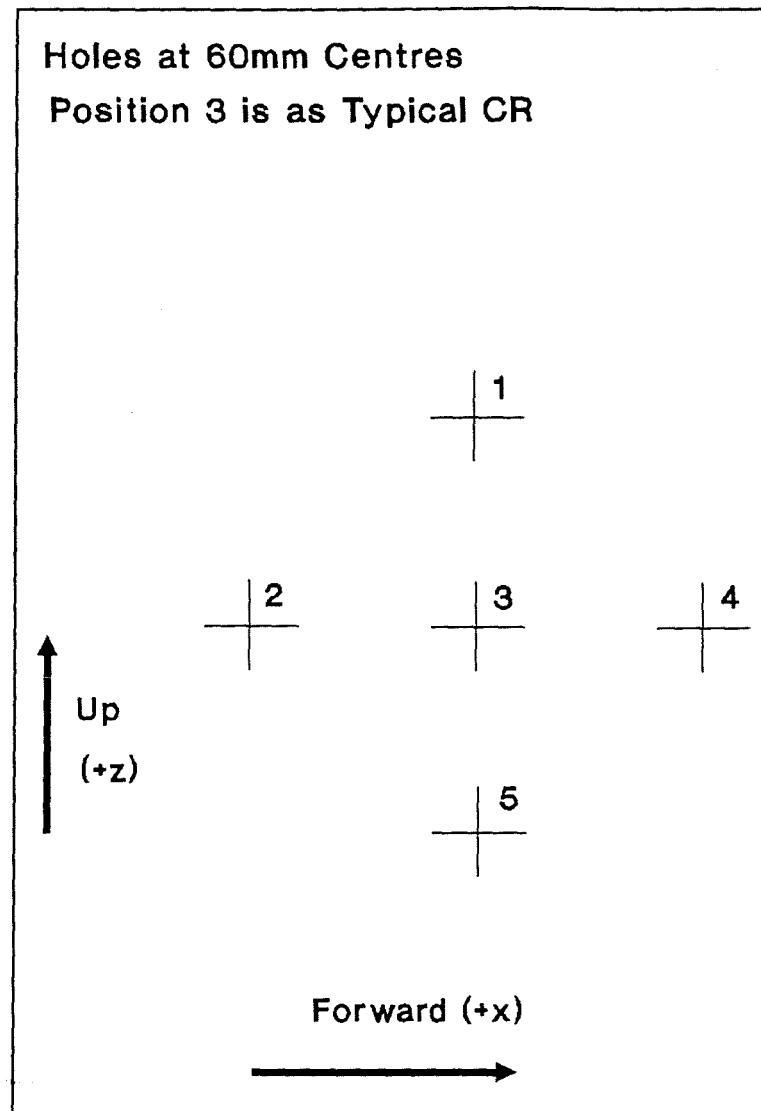


Figure 7.9. Lap belt positions

This phase of testing was not part of the work conducted under contract with the Transport Research Laboratory.

#### 7.6.1 RESULTS

As seen in many of the last 5 sections there is an difference observed between the lap belt and 3 point belt restrained cases. As they stand these results do not provide an adequate description of the effect of a variation in adult belt route and time and cost limitations precluded any further testing. However, these results are supported by computer simulation results which



are discussed in the next chapter. The results of the experimental testing are presented in the following two sections.

#### 7.6.1.1 THE LAP BELT RESTRAINED CASE

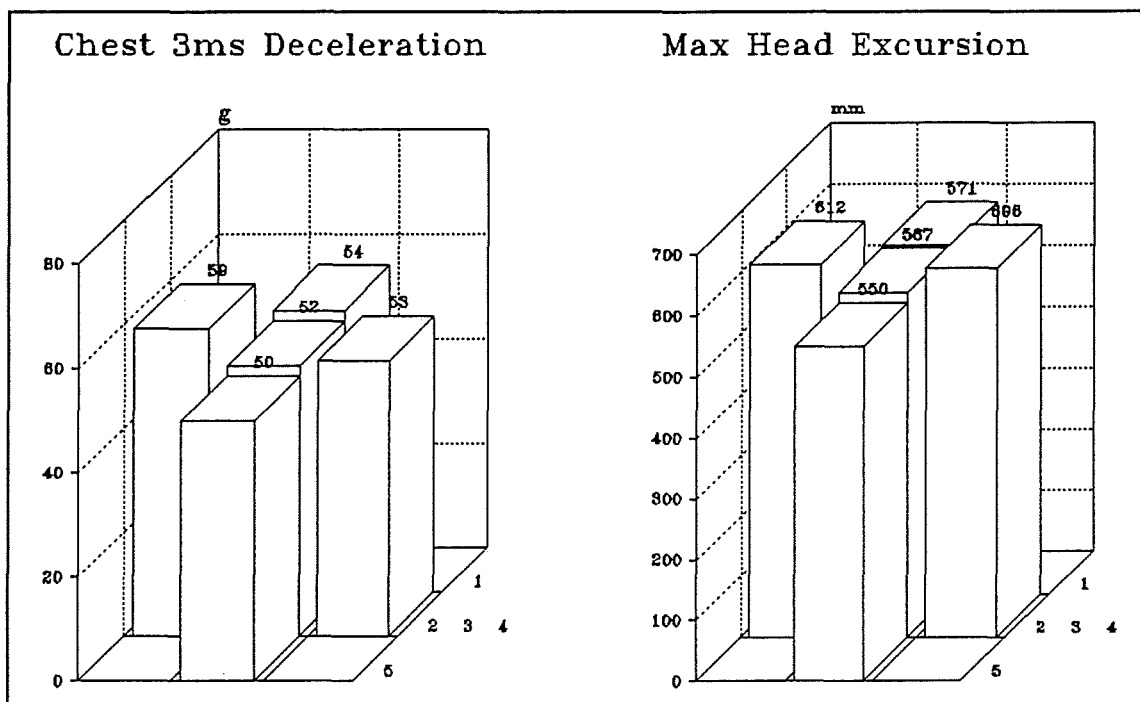


Figure 7.10. Adult belt route, Lap belt restrained results.

The empirical results, shown in Figure 7.10, together with an analysis of the high speed film record suggest two main effects of a variation of the belt route. Firstly, a variation in the translational movement of the child restraint and secondly an alteration in child restraint forward rotation. The increase in translational movement occurs when the initial belt angle to the horizontal is increased which occurs when the belt attachment to the restraint frame is moved back or up. This is because the child restraint, during the impact, attempts to pull the belt to a more horizontal position, which entails a greater forward movement for a larger initial belt angle. The increase in forward rotational movement of the child restraint occurs when the belt force is applied to a more forward or lower position on the child restraint frame. This is due to the increased moment of this

force and the child restraint inertial force acting through the centre of gravity.

When the belt attachment point was varied in a vertical plane from point 5 to point 1, these two effects appear to cancel each other out. When the attachment point was varied in a horizontal plane, from 3 to 2 or 3 to 4, the change in the lap belt angle was greater and the individual effects resulted in an increase in forward excursion away from the standard position, 3. These observations are based upon both these experimental results and the computer simulation results. Therefore reference should be made to the computed results in Section 8.1.

#### 7.6.1.2 THE 3 POINT RESTRAINED CASE

The 3 Point Restrained child restraint results did not exhibit the same characteristics as discussed for the lap belt above (see Figure 7.11). It is concluded that the restraining force of the diagonal strap nullifies any variation in the lap belt movement. The excursions were not significantly altered as the lap section was moved. The changes in acceleration which occurred are not easily explained but were not evident in the computer simulations. Therefore it is felt that these results were subject to experimental error and scatter.

### 7.7 OVERALL SUMMARY OF THE EXPERIMENTAL INVESTIGATION OF FCS DESIGN PARAMETERS

It has been shown that the effect of the variation of a particular parameter is dependent upon the adult restraint type. In addition, for many of the tests, the shell position in the frame differed between the lap belt and the 3 point belt

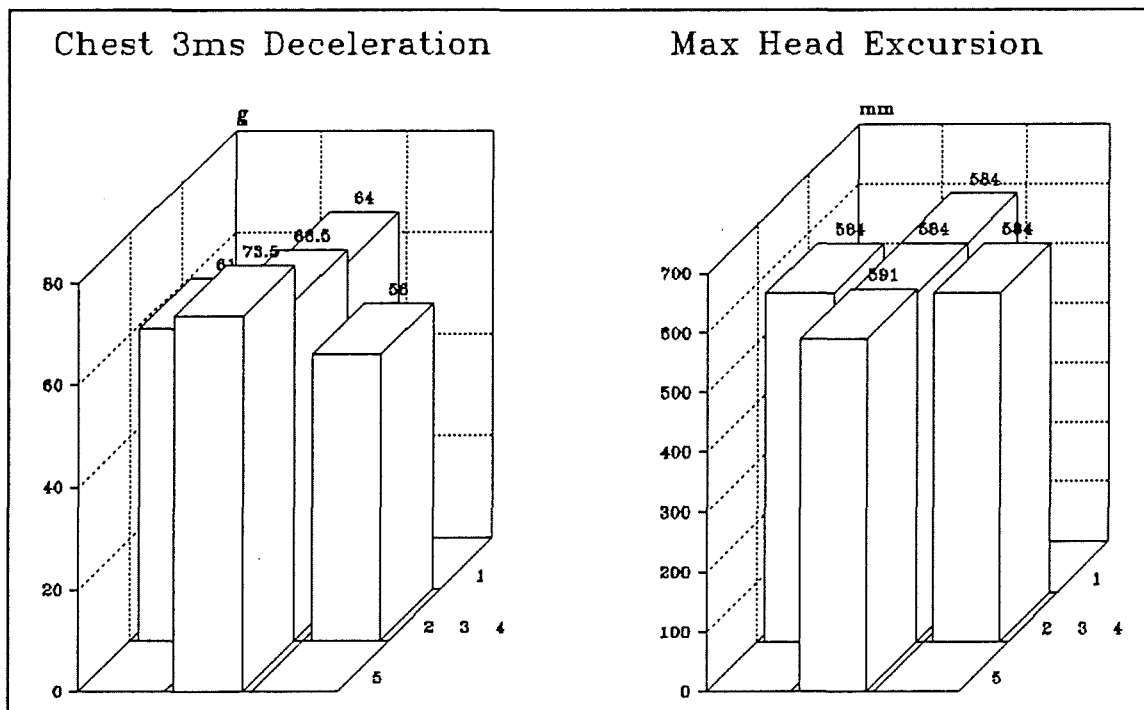


Figure 7.11. Adult belt route, 3 point restrained results.

configurations. Therefore the results for these two attachment configurations are considered separately.

#### 7.7.1 FRAMED CHILD SEAT ANCHORED WITH A LAP BELT

In the test phase which examined the importance of position of occupant centre of gravity there was not a very large effect on chest acceleration nor on head forward movement between the shell positions used. There was a slight trend to reduce chest acceleration and head movement with a lower and more forward location of the shell. However, the differences in the initial location of the head between the shell locations is much greater than any reduction in absolute movement. Consequently, forward excursion for the forward locations considerably exceed those for the rear locations. For instance the head movement with shell position 'g' was 480 mm in comparison with 420 mm for position 'i' while the head excursions were 419 mm and 535 mm respectively.

Increasing the foot contact area increases the forward excursion but decreases the chest acceleration, the largest foot producing the lowest chest acceleration of any test. Examination of the film records show that this is due to the higher initial compression of the test seat cushion with a smaller base area which therefore results in earlier 'bottoming out' of the cushion. With a large base area, greater dynamic compression of the cushion is available, resulting in a greater movement of the child restraint, larger head excursion but reduced chest acceleration. This raises the question of the importance of the representativity of the ECE R44 test seat design and initial installation procedures. From observation of real car seats and seat pans it is obvious that the ECE R44 is not a good representation of a typical car. Seat cushion depth varies across the rear seat section and thus the exact positioning of the child seat would be likely to effect the performance.

Reclining the shell in the frame about the lower mounting point led to a significant reduction in the head excursion and a small increase in chest acceleration. The test indicated a higher rebound acceleration for the head but it is not known whether this reflects what would happen to a child. The loading in the dummy's neck was thought to be increased in the reclined case, but due to instrumentation limitations this could not be examined experimentally. Therefore this possible factor in neck injury was examined using computer simulation (see chapter 11).

The addition of a top tether to the lap belt attached child restraint with the small bar foot resulted in only small reduction in both the chest acceleration and the head forward excursion. But, the effects were much greater for the SFCS

configured with a large area foot, reducing the head excursion from 532mm to 319mm, the lowest head excursion observed. However, this was at the expense of a large increase (approx 60%) in the chest acceleration. The difference in effects between these two base areas is also attributable to the high precompression of the test seat cushion with the small base area resulting in the main reaction force being provided by the test seat structure rather than the cushion for this configuration. As the reaction force for the child restraint with the larger foot comes from compression of the cushion, the addition of the top tether will have a greater effect, as observed. The relevance of this for use in cars will depend on the car seat design and the amount of precompression that parents apply in normal use. In view of the potentially large effect on head excursion with a top tether, it would be worth exploring the use of yielding top tethers to reduce the undesirable increase in chest acceleration observed.

The route of the lap belt was seen to affect the performance of the child restraint. Changes from the optimum position increased the forward excursion either through greater translational movement or rotation of the child restraint. Tests on the typical production child restraint showed that the specified belt route gave the optimum performance for the surrogate FCS.

#### **7.7.2 FRAMED CHILD SEAT ANCHORED WITH A 3 POINT BELT**

Movement of the shell within the frame produced small changes in both head movement and chest acceleration. There was a trend for the chest acceleration to be reduced as the shell was moved forwards and down. There was also an indication of a reduction in head movement as the shell was moved forwards and down which

was confirmed by a series of computer simulations. However, as with the lap belt tests, this reduction on head movement was swamped by the differences in initial head position relative to the test seat, resulting in a much greater head excursion as the shell was moved forwards. Again, the optimum position would appear to be as low and as far back in the frame as possible, although the surrogate seat design precluded testing in this location with the 3 point belt.

Changing the area of the base of the child restraint had little effect on the performance when using a 3 point belt suggesting that most of the restraint is controlled by the belt design and layout rather than interaction with the seat cushion.

As with the lap belt configuration, reclining the shell within the frame reduced head forward excursion but increased chest acceleration. Reclining about the lower attachment produced the greatest effect on both parameters. Again, there was an indication of greater head rebound violence with the reclined mode, but the significance of this for injuries in real children is not known.

Very little effect of the location of the lap section was observed on the head excursion when using a 3 point belt. Chest acceleration appeared to increase for lower attachment points of the lap belt and to decrease either side of the standard position. The significance and reasons for this are unclear and could be examined further with the aid of computer simulations.

Where it is possible to compare the performance of the child restraint between being held by a lap belt and held by a 3 point

belt, both the head excursions and the chest accelerations are similar or lower with the 3 point belt. The differences are not great but this may be a reflection of the test seat and the installation conditions. The differences when installed realistically in cars should be explored.

8 RESULTS OF A COMPUTERISED STUDY  
OF THE EFFECT OF CHILD RESTRAINT  
DESIGN PARAMETERS ON THE  
DYNAMIC PERFORMANCE



## 8 RESULTS OF A COMPUTERISED STUDY OF THE EFFECT OF CHILD RESTRAINT DESIGN PARAMETERS ON THE DYNAMIC PERFORMANCE

This chapter, like the last, describes work which was conducted to identify which of the framed child restraint design parameters are critical in defining the dynamic performance. Unlike the previous work, the investigation presented here was conducted using computerised Crash Victim Simulation (CVS) techniques rather than experimental tests. The simulation technique and modelling package (MADYMO3D) have been defined in previous chapters. This chapter will discuss the research programme that has been conducted and the subsequent results.

The programme of CVS work included the re-examination of most of the parameters that had been investigated experimentally. This parallel method of investigation provided both a validation of the CVS technique and a useful confirmation of the experimental results. In addition to the repeat work, the use of CVS allowed the examination of many parameters which were not able to be investigated experimentally. Parameters such as FCS mass and Centre of Gravity are not easily varied independently on an actual child seat. However, in a mathematical model one individual parameter can be easily be varied by a change in numerical values, and therefore a true parametric study can be achieved.

The design features of framed child seats (FCS) that were examined were as follows;

- 1) Variation of adult belt route on FCS frame
- 2) Variation of system centre of gravity via a change in seat shell position.
- 3) FCS foot size

- 4) Seat shell inclination
- 5) Effect of a top tether
- 6) Harness stiffness
- 7) Harness slack
- 8) Seating shell stiffness
- 9) FCS mass
- 10) FCS centre of gravity position
- 11) FCS moment of inertia

Parameters 1 to 5 comprise the parallel CVS and experimental study and will be discussed in the first five sub-sections. The remaining features will be discussed in the later sub-sections. Where appropriate the simulations were conducted of both the lap belt restrained FCS and the 3 point restrained FCS. The models were all based upon the surrogate framed child seat that was used in the experimental study.

The use of the MADYMO3D software allowed the injury potential to be assessed using injury indicators other than those which could be measured in the experiments. Neck axial load was one of these factors. The axial load in any element can be output by MADYMO. The Neck Axial Load was taken as a comparative indicator of possible increases in the potential for neck injury. No attempt was made to infer actual injury levels as the neck model used in this part of the study was not considered to be a good representation of the human neck.

The following sections discuss the detail of each parameter investigation in turn, together with the results.

### 8.1 ADULT BELT ROUTING AROUND THE FCS FRAME

The exact routing of the adult belt through the frame of a child seat varies between different manufacturers designs. There is no route defined in any standard, the only limits on the routing are from the geometry of the vehicle and the performance of

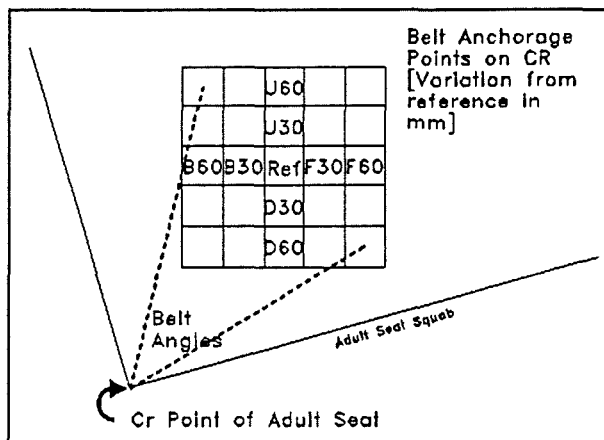


Figure 8.1 The 25 FCS belt route positions

the child restraint. In addition variations in the belt route on a particular design of seat can occur due to the individual car geometry in which it is fitted and misuse of the seat by the user. Thus the effect of different belt routes on the FCS performance was an important parameter to study. The results of the experimental study (see section 7.6.1) were affected by experimental scatter and limited by the number of test runs which could practically be conducted. Computerised crash victim simulation does not suffer from experimental error or scatter and is a faster and more cost effective technique for a parametric study such as this.

34 simulations were conducted, 25 lap belt restrained and 9 3 point restrained cases. In the 3 point restrained simulations, as in the experimental tests, only the lap section of the belt route was varied. Variations in diagonal strap route are very limited by the child seat geometry (the belt must pass between seat shell and frame near the top of the seat). It was therefore considered inappropriate to investigate variations in diagonal belt position as such movement would on the whole lead to impracticable belt routes.

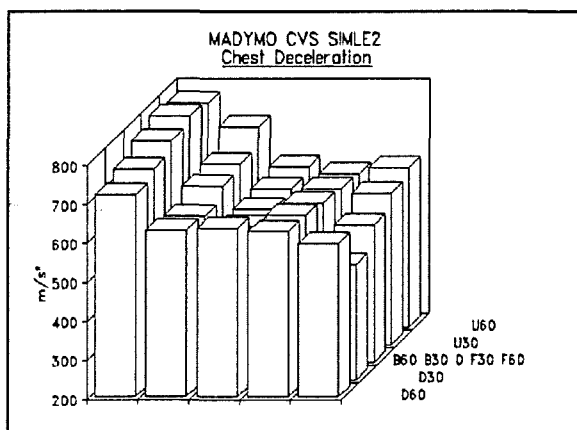
Belts in the MADYMO3D code are represented by non-linear spring-damper elements between two mass elements. A series of belt elements can be defined in one command to simulate the various sections of a seat belt. Slip between elements, slack and pretension can all be included in the model. The lap belt around the child seat was simulated by a two element belt model, one element on each side of the seat, attached to a point on the FCS rigid body and the vehicle system. The belt attachment point on the FCS was then varied over 24 positions around the central reference position (Figure 8.1). The reference position was as measured on the Britax 2-way child seat. The resulting effect of this route variation is discussed in the following two subsections which present the two restraint cases (lap and 3 point) separately.

#### 8.1.1 THE LAP BELT RESTRAINED FCS

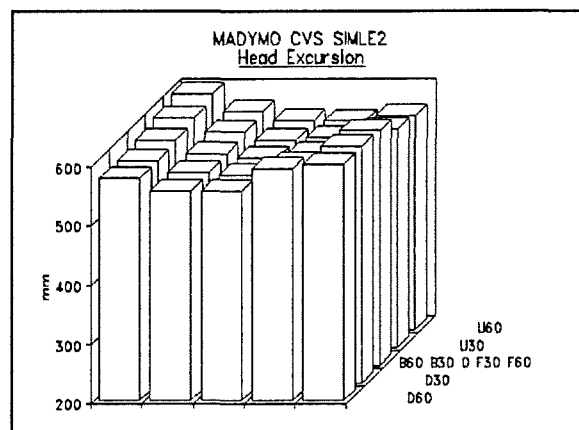
The Lap Belt Restrained child restraint results shown in Figure 8.2 and Figure 8.3 together with an analysis of the graphical output (Figure 8.4) suggest that there are two main effects of an alteration in belt route; a variation in the translational movement of the child restraint and an increase in child restraint forward rotation. The increase in translational movement is induced when the initial belt angle to the horizontal is increased. This occurs when the belt attachment to the restraint frame is moved back or up from the reference position. This is because the child restraint, during the impact, attempts to pull the belt to a more horizontal position, which entails a greater forward movement for a larger initial belt angle. The increase in forward rotational movement of the child restraint occurs when the belt force is applied to a more forward or lower

position on the child restraint frame than the reference position. This is due to the increased moment of this force and the child restraint inertial force acting through the centre of gravity. The irregularity of the chest decelerations in the far forward and down positions is due to the excessive rotation (actual flipping over) of the FCS when the belt is routed in this position.

When the belt attachment point was varied in a purely vertical plane through the reference (central) position, these two effects appear to cancel each other out (no apparent alteration in the head excursions). However, when the attachment point was varied in a purely horizontal plane through the reference position, the change in the lap belt angle was greater, and the individual effects resulted in an increase in forward excursion away from the standard position.



**Figure 8.2** 3ms Chest decel variation with belt route



**Figure 8.3** Head excursion variation with belt route

Thus the variations in the head excursions shown in Figure 8.3 are explained by alterations in the child seat movement. When examining the chest decelerations there was not an inverse relationship with the excursion variation as we might expect (larger movement - lower deceleration and vice-versa). However,

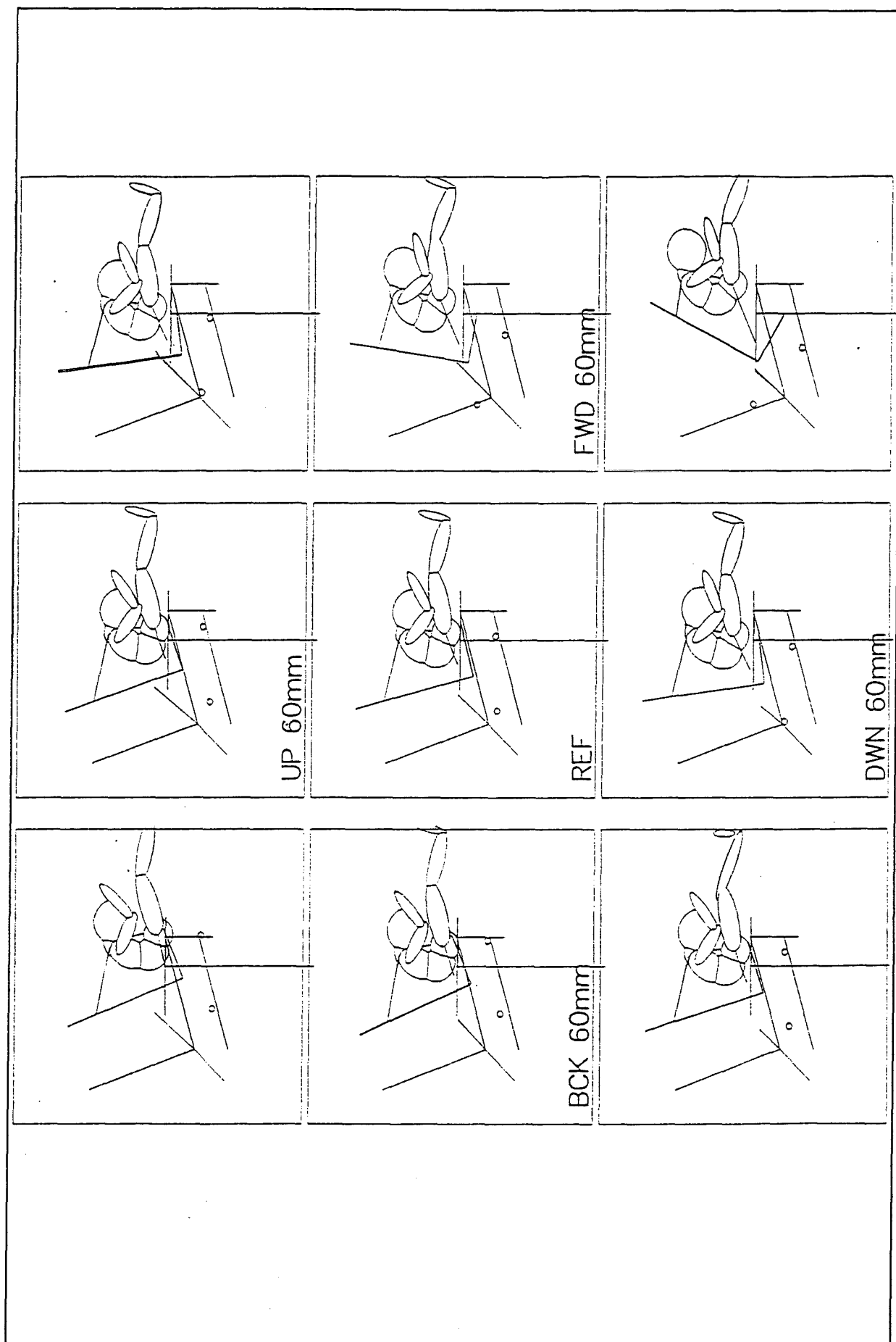
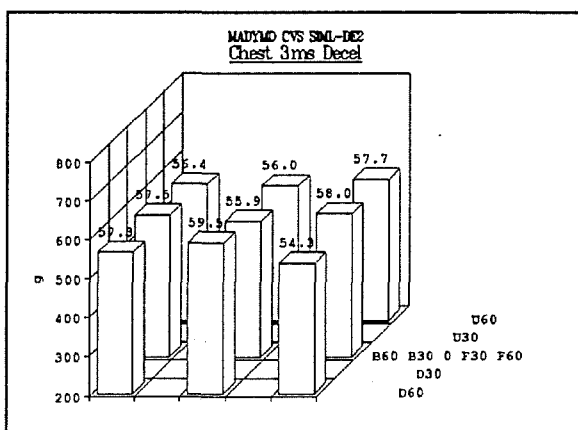


Figure 8.4 Lap belt restrained FCS CVS. Frames of nine extreme belt route positions at t=120ms

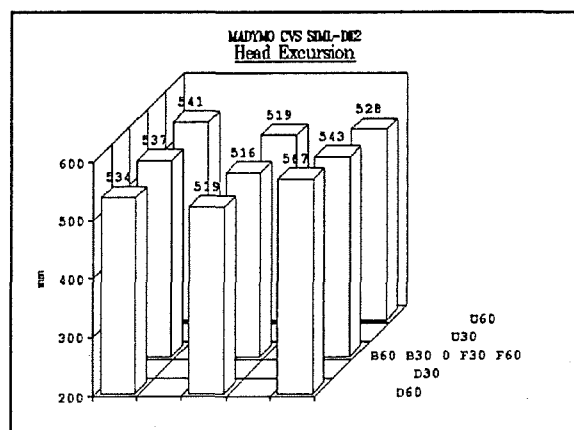
this did not mean that the laws of physics did not apply, just that: 1) Head excursion was not equal to the stopping distance of the occupant, it was actually stopping distance plus a period of free-flight whilst the belts were straightened ; and 2) only the peak value of chest 3 ms deceleration was measured, which was subject to spikes when impacts occur between body, FCS and adult test seat.

### **8.1.2 THE 3 POINT RESTRAINED FCS**

The simulation programme was conducted in the same manner for the 3 point restrained FCS configuration as for the lap belt. The 3 point restrained FCS was found to be less sensitive to a change in the lap section routing and therefore only the extreme belt route positions were simulated.



**Figure 8.5** Belt Route Variation on FCS. CVS 3ms chest decel results.



**Figure 8.6** Belt route variation on FCS. CVS head excursion results

Figure 8.5 shows the chest deceleration results and Figure 8.6 the head excursions. Both graphs are similar in form to the lap belt restrained results discussed in the last section. However, the extent of the effect of a variation in lap belt route was not as marked as for the previous case. This was due to the restraining influence of the diagonal belt, which reduced both the rotation of the FCS and its lateral movement.

## 8.2 EFFECT OF A VARIATION OF SEATING SHELL POSITION

This parameter was another of those that were previously investigated on the RSEL experimental impact test rig. The position of the plastic seating shell within the frame varies between child seats. There are some limiting factors on the position of the shell, namely: space for the adult belt to pass through the frame; geometry of vehicle seats; child seating comfort and other ergonomic considerations. However, it was found that it was possible to vary the position on the surrogate child seat whilst satisfying most of the criteria mentioned. The surrogate child seat was modelled with the shell in the same positions as used in the experimental work (see Section 7.2). And similarly the surrogate FCS was modelled whilst restrained by both a lap and 3 point belt. The results follow in the next two sections.

### 8.2.1 THE LAP BELT RESTRAINED FCS

When the shell position was varied within the FCS frame in the simulations a similar effect to that seen in the experimental work was observed. Head movement exhibited the largest changes due to the variation

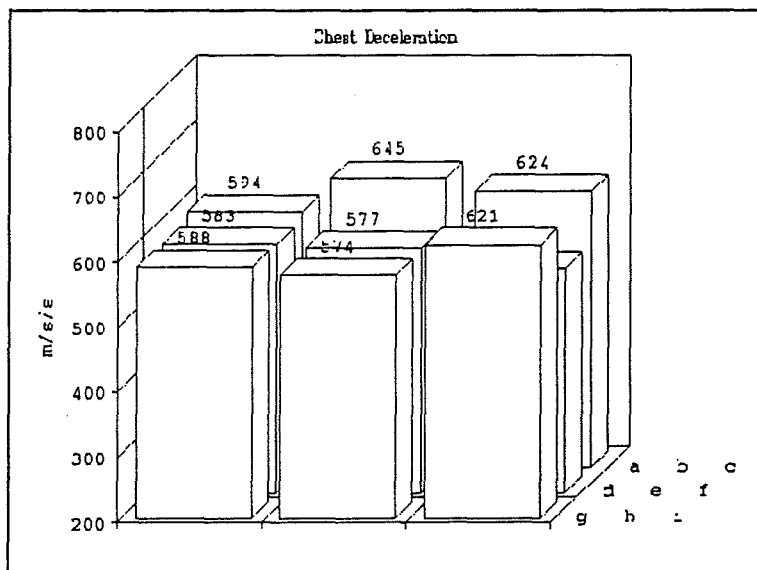
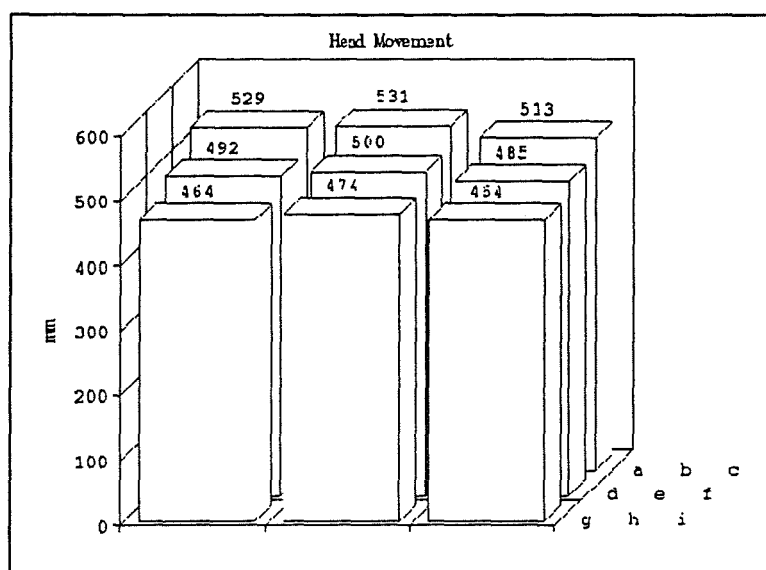


Figure 8.7 Effect of Shell Position on 3 ms Chest Decel. Lap Belt Restrained CS.

(Figure 8.8). As the shell position was moved up, the head movements increased due to the increasing distance from the centre of rotation (somewhere close to the belt anchorage). The



MADYMO results were more stable as the shell position was moved forwards and back than that seen in the experimental work. This



**Figure 8.8** Effect of shell position on max head movement. Lap belt restrained CS

can be partially attributed to the lack of experimental error, but is also due to the method of head movement measurement. In the experimental work the maximum forward point of the head can be assessed by the person

conducting the measurements. This point can be any point the head, but is usually on the top surface. The head of the test dummy is not elliptical as modelled in MADYMO but a more human-like shape. Therefore the point considered to be the maximum forward excursion of the head can vary around the head profile with head and neck angle. In a MADYMO simulation the user must specify points on the head for which positional output is required. This point was chosen as the top of the ellipsoidal head and could not be altered. Therefore discrepancies between the experimental and computer simulation results were expected.

The chest 3ms decelerations (Figure 8.7) show, with the exception of a couple of points, similar form to the experimental results. There is a trend for slightly higher decelerations as the shell is moved upwards. The effect of a horizontal movement of shell is less clear, the decelerations vary but show no clear pattern. However, The lower rear position (g) was considered to be the optimum position, based upon low values of chest deceleration and

head movement. This again was in keeping with the experimental results.

### 8.2.2 THE 3 POINT RESTRAINED FCS

The shell position of a 3 point belt restrained FCS is greatly limited by the belt itself. Space is required behind the shell in which to route the two sections (lap and shoulder) of the 3 point belt. Thus

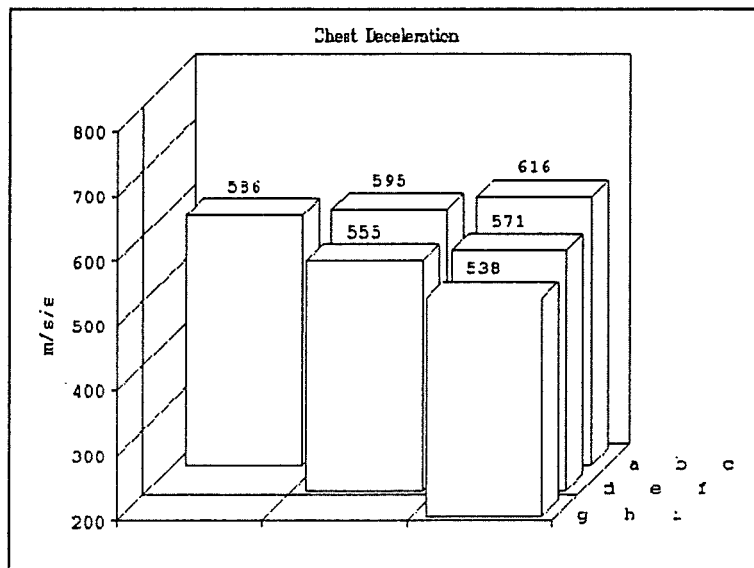
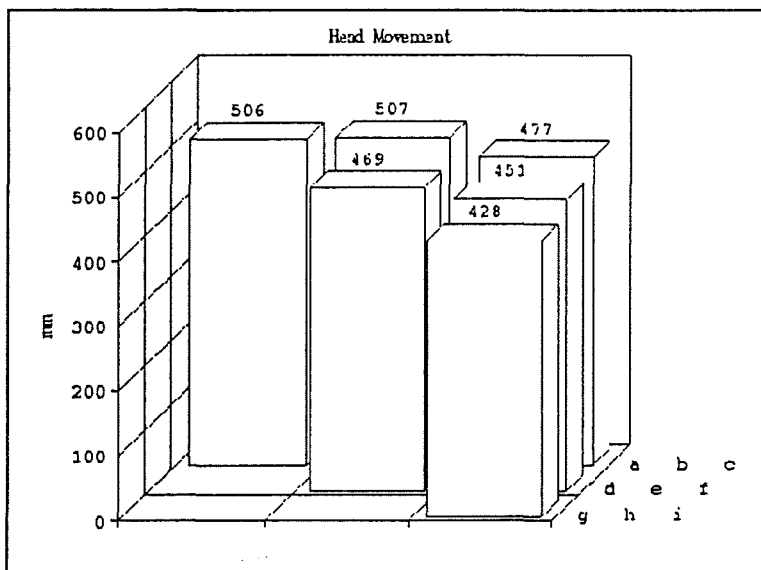


Figure 8.9 Effect of shell position on 3 ms Chest Decel. 3 point belt restrained for the experimental CS.

test work only six of the nine shell positions were physically possible. It was considered inappropriate to simulate the other three positions in the MADYMO CVS work, as it would be a purely academic exercise with little practical application. The effect of a variation of shell position on chest 3ms deceleration is shown in Figure 8.9 and head movement in Figure 8.10.

Chest deceleration appears to follow a consistent pattern of change as the shell position is moved. Increases of up 8 g can be observed as the shell is moved up (from position i to position c). Similarly the chest deceleration increases as the shell is moved forwards, although the increase is smaller. The latter effect is in contradiction to that of the experimental results, which appeared to show chest deceleration falling as the shell position was moved forward. This difference could be explained by rogue experimental results. If two of the experimental results



**Figure 8.10** Effect of shell position on max head movement. 3 point belt restrained FCS

were incorrect (those of positions a and c) then the experimental results would compare more favourably with the CVS. In order to test this theory many experimental runs would have to be conducted with the shell in each

position. This was not feasible in this project due to limited time and resources.

The head movement results were similar to those observed for the lap belt restrained case and the previous experimental results. Head movement is shown to increase as the shell position is moved upwards and rearwards. The explanation for the reduced head movement in the more forward shell positions is in the location of the occupant relative to belt route and anchorage positions. The child restraint can be seen to move forward and rotate during the impact. The rotation phase of occupant and restraint is reduced in the more forward positions because the occupant is closer to the final forward and down position, to which the occupant must move. The CVS results show that the choice of shell position i as the optimum position in the experimental work was sensible. This position exhibits both the lowest chest deceleration and head movement.

### 8.3 EFFECT OF A VARIATION OF FOOTPRINT AREA

This area of the investigation was the only section where the computer simulations failed to model the changes in FCS performance which were observed in the crash tests.

The experimental work has already been discussed in Section 7.3. The increase in footprint area of a lap belt restrained FCS was found to decrease the chest deceleration and increase head excursion. This was due to an increase in translational movement of the FCS and a greater depth of squab through which the FCS could decelerate.

The increase in foot size was modelled in MADYMO by the introduction of two larger feet into the FCS model. Two long thin ellipsoids were added to simulate the largest foot used in the experimental work. The interaction of these feet and the squab had to be redefined and experimental tests of squab stiffness were conducted in order to gain information for the model (see Appendix C). The experiments took the form of a quasi-static crushing of a sample of seat squab foam, over an area equal to the footprint size. The result of these tests was a force-deflection curve for the total foot area when pushed into the squab in a normal direction. The force for a given deflection was then halved for input to the model, as each of the two ellipsoids which represented the foot was defined as having half the total area.

In addition to the changes in foot representation, alterations were also made to the FCS mass, centre of gravity and moment of inertia. The actual measured values from the surrogate FCS were used.

The resulting chest decelerations obtained in this simulation did not differ significantly from the standard bar foot case and the FCS did not noticeably alter its kinematic response. The explanation for this lack of effect was thought to be a poor representation of the foot-squab interaction in the model and thus an attempt at a better contact representation was made. The model was altered by splitting the foot into ten elements. It was considered that dividing the foot contact in this way would closer represent the actual distributed contact forces. However, no significant effect on the FCS response was achieved.

There are several possible explanations for this lack of change in FCS model performance. Firstly, there is the possibility of inaccuracy in the measurements of seat squab stiffness. The squab was measured statically and it is not known whether the foam material stiffness alters with strain rate (damping). In addition the squab stiffness was measured with the whole foot area penetrating the squab in a normal direction. No measurements could be made for an angled penetration. The second explanation lies in the representation of the contact by MADYMO. Section 2.3.1 has already outlined how MADYMO calculates contact forces. This is a gross simplification of such dynamic interactions which takes no account of the tangential forces that can be applied by a penetrated material, such as squab foam. Another explanation for the discrepancies between the test and CVS results is that the FCS was modelled in these simulations as a rigid body. In fact small plastic deformation of the surrogate FCS were observed after tests were completed. In particular the front section of the plate foot of the FCS was often bent upwards and had to be straightened. This flexibility in the structure could not be easily modelled in MADYMO, but would be likely to contribute to

the lower chest decelerations observed in the tests.

#### **8.4 EFFECT OF AN ALTERATION IN SEAT SHELL INCLINATION**

The experimental work which investigated the effect of seat shell inclination (see Section 7.4), highlighted a possible neck injury mechanism. The neck representation in MADYMO P3 dummy database was not considered to be suitable for examining this potential problem. Therefore the investigation of the effect of seat inclination was delayed until the neck representation was improved. Section 11.2.4 discusses the investigation into this subject within the chapter specifically concerned with work conducted with the improved neck model.

#### **8.5 EFFECT OF A TOP TETHER**

The experimental work conducted to investigate the effect of a top tether did not show any constructive effect on the occupant's response, however it was considered appropriate to check this result using the CVS technique. A top tether was modelled by adding a third belt section to the upper part of the model in a position equivalent to that of the experimental test. The belt section was assigned the same force-deflection characteristics as the adult belt straps (adult webbing was used in the test). The model was set up with the same surrogate FCS configuration as used in the test ie; bar feet with shell in position g.

The IPI for the top tether and no top tether case are compared in Table 8.i. It can be seen that the use of a top tether reduces all of the IPI.

Head excursion is reduced due to the reduction in FCS rotation and translational movement caused by the introduction of the

Table 8.i. Top tether results

Tether ?	Chest 3ms Decel (m/s/s)	Head Exc (mm)	Neck Load (N)	HIC
No	593	469	1941	959
Yes	429	395	1386	542

upper restraint. In addition chest 3ms deceleration is reduced as the occupant is more rigidly restrained and therefore has a shorter 'free flight' period and is decelerated more with the vehicle.

The test results discussed in Section 7.5 suggested that a top tether has little effect on a lap belt restrained FCS. There is an obvious inconsistency with the simulation results discussed above. This could be due to one or a combination of the following factors:

- Experimental error in the test
- Webbing slip and FCS flexing in the test reducing the effect of the tether
- Modelling assumptions reducing the accuracy of the model

It is thought that the second of these factors is the most likely and predominant factor.

#### 8.6 EFFECT OF HARNESS STIFFNESS

The tensile strength and width of the harness webbing used in a FCS is defined in most of the international standards, however unlike adult belt the stiffness of the harness is not directly defined. It was considered that a variation in harness stiffness would cause a considerable change in the dynamic response of the occupant. Logic tells us that if the harness stiffness is reduced

the occupant will move further but will be decelerated at a lower level.

$$\begin{aligned}\Sigma F - Kx &= ma \\ \Rightarrow K &\propto \frac{a}{x}\end{aligned}$$

**Equation 8.1** Relationship between harness stiffness (K), occupant deceleration (a) and movement (x) based upon simple rigid body model

If the occupant is considered as a single rigid body and harness restraint as a single force the relationship between acceleration, movement and harness stiffness can be quoted as shown in Equation 8.1. A balance must therefore be made between movement and deceleration in order that the possible injury from deceleration can be limited, without direct impacts on the occupant with the vehicle structure. The purpose of the simulations conducted in this study was to examine this relationship. The harness stiffness was varied by multiplying the typical value by the following factors: 4, 2, 0.5 and 0.25. The simulations were conducted for lap belt restrained and 3 point restrained and the results are discussed in the following two sections.

#### **8.6.1 THE LAP BELT RESTRAINED FCS**

Figure 8.11 shows the results of a variation in harness stiffness for the lap belt restrained FCS. The expected relationship of an increasing deceleration (chest 3ms) and decreasing movement (head excursion) with and increasing stiffness can be observed in these results. In addition the more formalised relationship of Equation 8.1 can be seen to operate. For example, if harness stiffness is reduced by half, the excursion according to Equation 8.1 would have to increase twice the magnitude of the acceleration decrease. The order of the acceleration and

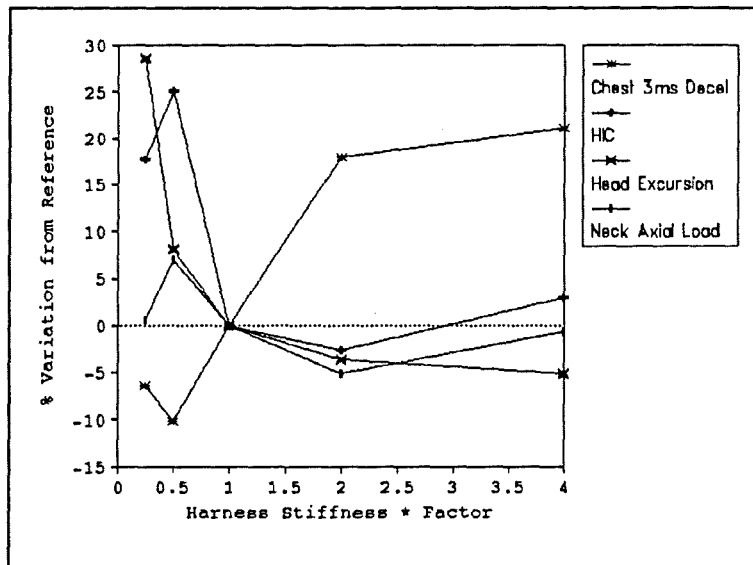


excursion changes can be seen to approximately agree with this theoretical treatment.

HIC is shown to be altered in an opposite manner to the chest

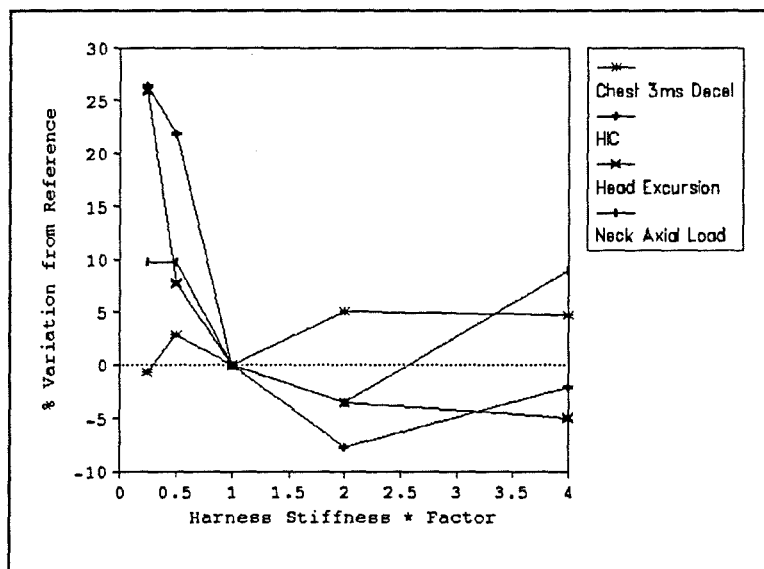
deceleration. This is due to the fact that

HIC is based upon both the acceleration magnitude and duration. The latter of which is increasing as harness stiffness is decreasing.



**Figure 8.11** The effect of harness stiffness on the performance of a lap belt restrained FCS

#### 8.6.2 THE 3 POINT RESTRAINED FCS



**Figure 8.12** The effect of harness stiffness on the performance of a 3 point restrained FCS

The 3 point restrained results can be seen to vary in a similar manner to the lap belt restrained case (Figure 8.12). One unexplained result is the slight increase in 3ms chest deceleration for a harness stiffness of

half the standard. It is thought that the explanation lies in the peakiness of the occupant decelerations which mask the underlying trends.

## **8.7 EFFECT OF SLACK IN THE HARNESS**

It is generally accepted that slack in any occupant restraint reduces its effectiveness. The slack in the belt allows a longer period of occupant 'free flight'. When the slack is taken up the relative velocity between vehicle and occupant will be greater and thus there is a greater jerk on the occupant. Any velocity dependent feature of the harness webbing (which is likely to make the effective stiffness higher) will also come more into play. In addition to increases in occupant deceleration the occupant excursion will be increased, roughly in proportion to the amount of slack.

This section of the study comprised a quantification of the effect of slack on the surrogate FCS modelled. Three levels of slack in the shoulder straps of the FCS harness were simulated 0, 29 and 60 mm. 29 mm was the standard slack as measured in the actual surrogate FCS after it had been set up according to the ECE R44 test specification, and it was the level of slack modelled in all other MADYMO3D models presented in this thesis.

### **8.7.1 THE LAP BELT RESTRAINED FCS**

The effect of slack on the four injury potential indicators considered in this study is shown in Figure 8.13. As expected head excursion and chest 3ms deceleration were shown to increase with slack. However HIC was shown to increase when the slack is either increased or decreased from the standard 29 mm value. A slight increase in neck load was also noted for the zero slack case. The reason for the two increases with reducing slack is the increase in head rotation due to the greater restraint of the occupant's torso. With slack reduced the torso was more rigidly

held and the rotation of the head was increased. This caused increased centripetal accelerations and thus higher HIC and neck loads.

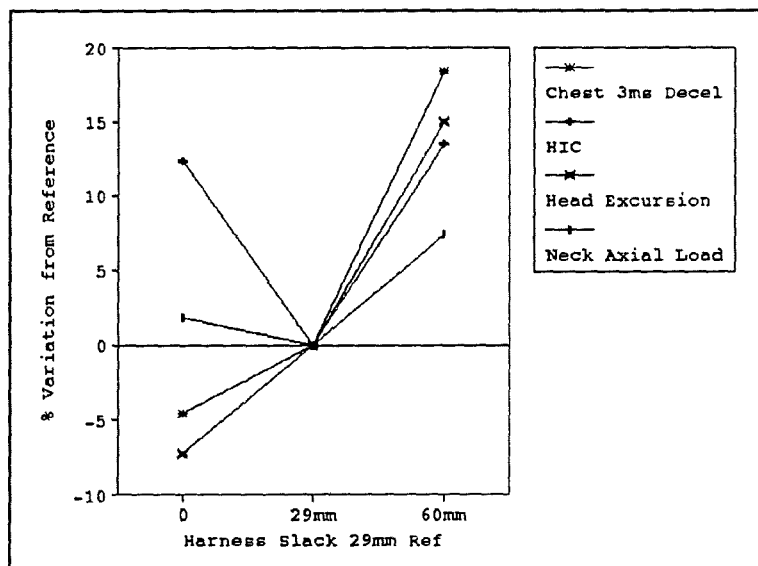


Figure 8.13 The effect of harness slack on a lap belt restrained FCS

### 8.7.2 THE 3 POINT RESTRAINED FCS

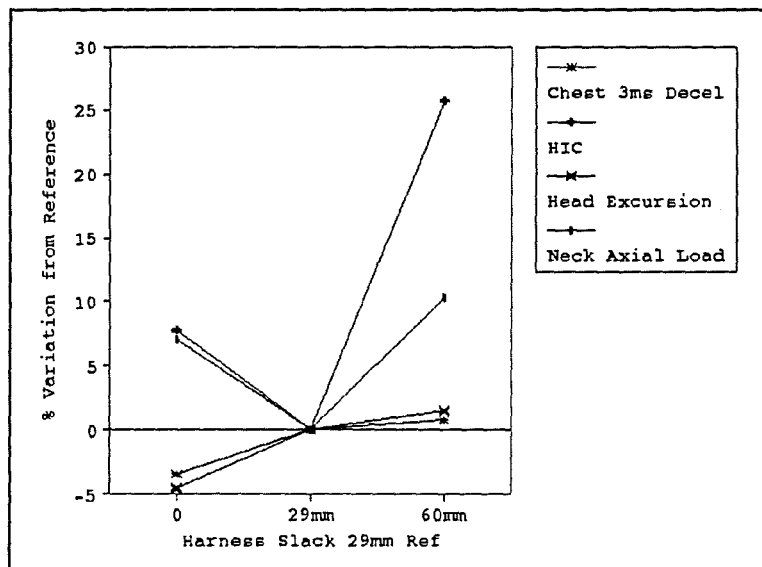


Figure 8.14 The effect of harness slack on a 3 point restrained FCS

A similar response to the lap belt restrained FCS was observed for the 3 point restrained FCS (Figure 8.14). Although the excursions and decelerations were not influenced to the same extent.

### 8.8 EFFECT OF SEATING SHELL STIFFNESS

The effect of seating shell stiffness was examined by varying the magnitude of the force in the occupant-shell contact interaction force-displacement curve. Thus this study investigated the effect of the interaction between occupant and shell. No consideration was given to the possible effect on the shell flexibility in relation to the FCS frame or harness. MADYMO is not an

appropriate tool for an investigation of this type.

The occupant-shell contact interaction force-displacement curve was varied in a similar manner to the harness stiffness investigation discussed in Section 8.6. The force curve was multiplied by factors of 0.25, 0.5, 2 and 4 and the results compared with the standard case for the lap belt restrained and 3 point restrained surrogate FCS.

#### 8.8.1 THE LAP BELT RESTRAINED FCS

The variation of shell stiffness was shown to have little effect on either head excursion or chest 3 ms deceleration (chest deceleration increased 5% for a 400 % increase in shell stiffness, see Figure 8.15). However,

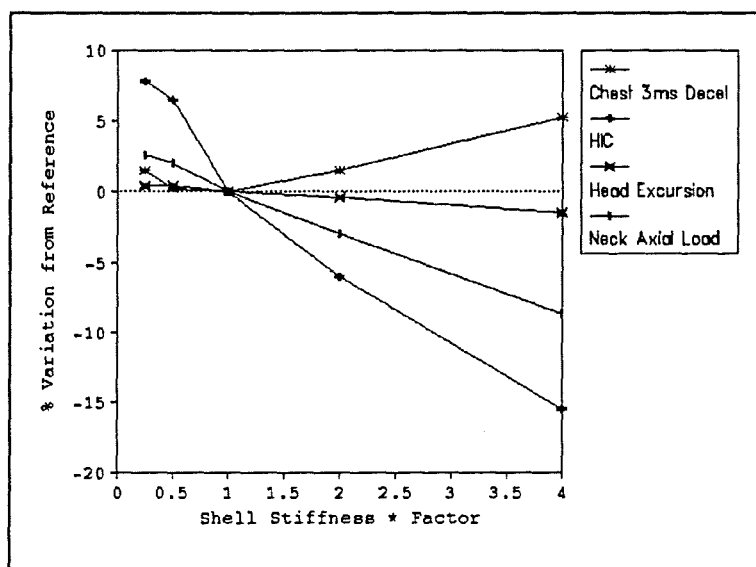
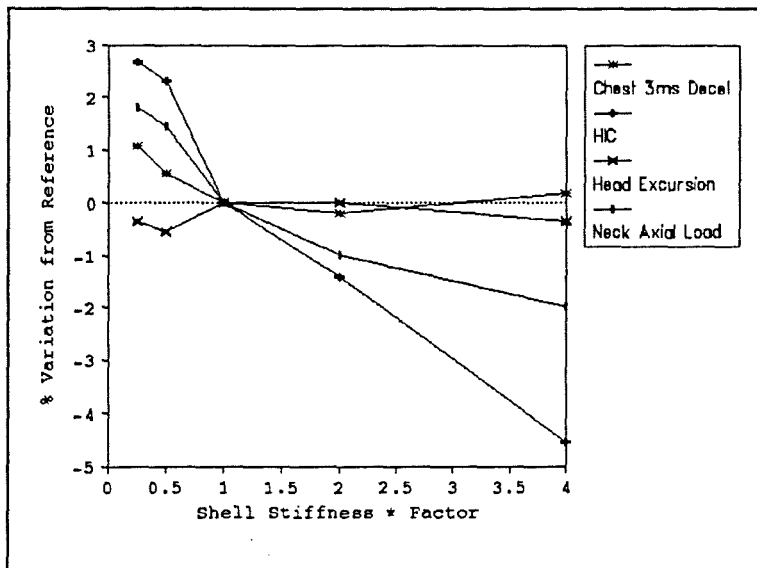


Figure 8.15 Shell stiffness effect on occupant of lap belt restrained FCS

the dynamic response of the occupant's head was affected. HIC and Neck load were shown to decrease when shell stiffness was increased. The exact reasons for the latter effect were not clear, but were not pursued further as the neck representation was not considered to have good biofidelity and no chin-chest contact was included in these models.

#### 8.8.2 THE 3 POINT RESTRAINED FCS

The injury potential indicators, of an occupant of a 3 point restrained surrogate FCS, were not affected by a change in shell



**Figure 8.16** The effect of shell stiffness on a 3 point restrained FCS

stiffness to the same extent as for the lap belt restrained FCS. Figure 8.16 shows that the largest variation in any of the IPI was under 8 % for a total variation in the standard shell stiffness of -75% to +400%. The same

pattern of variation occurred for the 3 point restrained FCS as the lap belt case, but the magnitudes were approximately halved. The shoulder strap of the 3 point belt provides an additional restraint on FCS rotation. If the rotation, and therefore downward occupant motion, is reduced, then the interaction between occupants pelvic region and seat shell will be less. Therefore the effect of changes to shell stiffness would be expected to be less marked.

### **8.9 MASS OF CHILD RESTRAINT**

The mass of a FCS is a parameter which could be minimised by introducing different materials into the design. In order to assess whether this is necessary, or indeed advisable, the effect of the mass of the FCS on the dynamic performance was examined. The mass was varied both positively and negatively in 1 Kg increments, about the reference surrogate FCS mass of 7.5 Kg. The total range of FCS masses which were modelled was 4.5 to 10.5 Kg and was considered to encompass most production framed child seats. Simulations were conducted for both lap belt and 3 point belt restrained FCS.

### 8.9.1 THE LAP BELT RESTRAINED FCS

The effect of a change in mass of a lap belt restrained FCS is shown in Figure 8.17. chest 3ms deceleration is shown to increase as the mass is increased. However for the total change of 6 Kg the chest deceleration was only

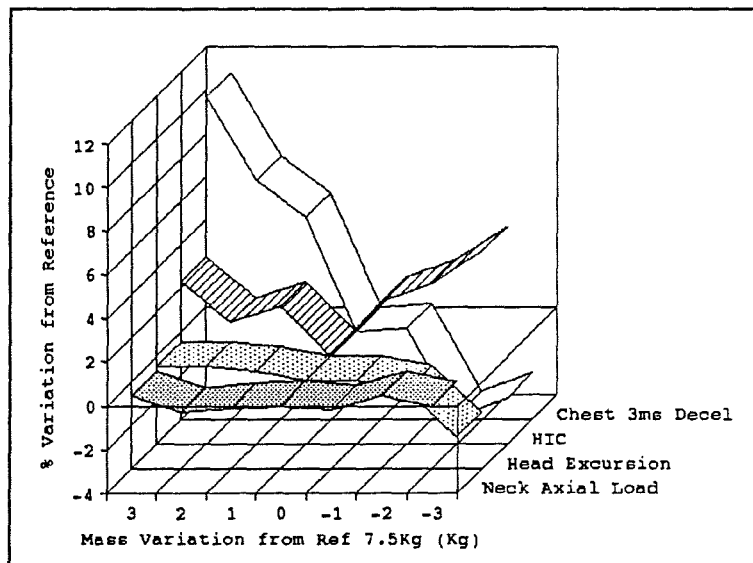
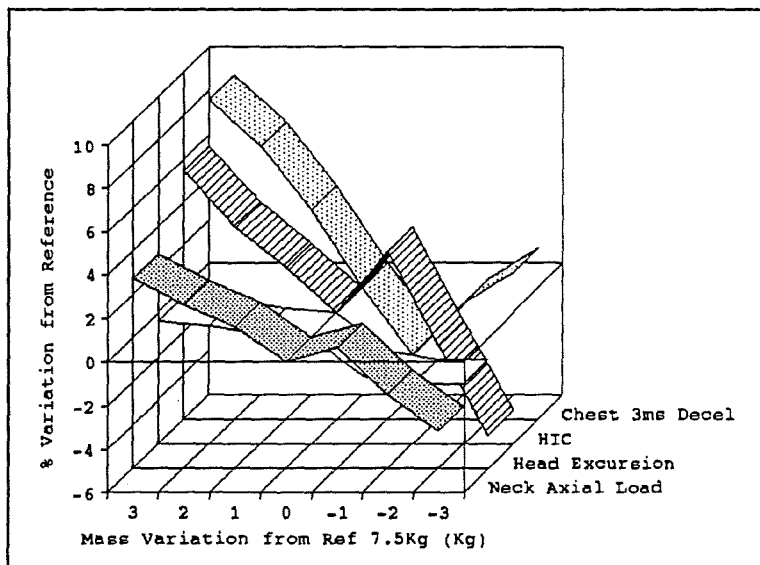


Figure 8.17 Variation of FCS mass results.

altered by 14% (approx 9g). The other injury indicators were not greatly affected, but all showed some increase for the heavier than standard masses. These results would suggest that a reduction in FCS mass alone would not provide an important method of limiting injury in lap belt restrained framed child seats. However, a reduction in mass does have some positive effect on most of the injury indicators and there are benefits to the users (the parents) who have to carry the device.

### 8.9.2 THE 3 POINT RESTRAINED FCS

The effect of mass variation on the 3 point restrained FCS is shown in Figure 8.18. A general reduction in injury potential indicators can be observed as mass is decreased. The reason for the decrease is a change in the FCS dynamics induced by mass changes. A lighter seat will respond more quickly to changes in vehicle velocity (the natural frequency of belt-FCS oscillation is higher). Thus the occupant is decelerated more with the vehicle and vibration effects have a less important role.



**Figure 8.18** Effect of variation of FCS mass. 3 point restrained FCS.

## 8.10 EFFECT OF FCS CENTRE OF GRAVITY POSITION

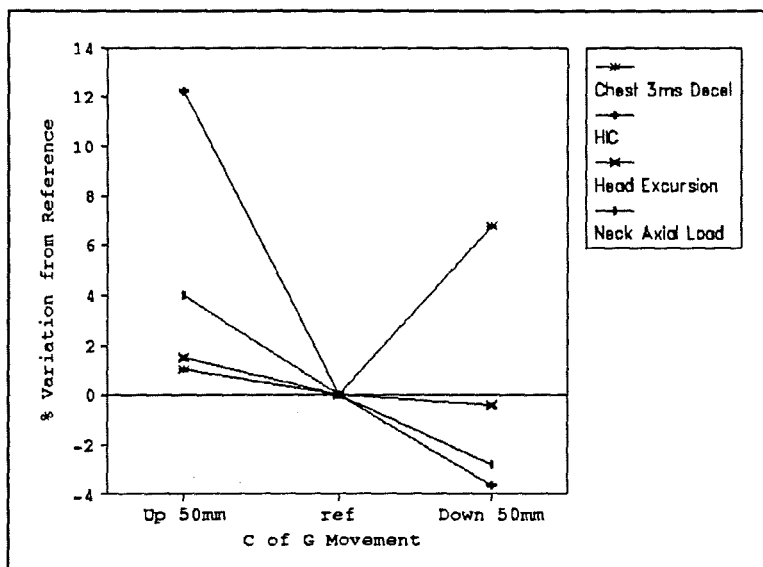
In addition to a change in centre of gravity due to a change in shell (occupant) position, the effect of a pure change in surrogate

FCS centre of gravity

was examined. The location of an element's centre of gravity is part of the required data in a MADYMO input deck. Therefore is relatively simple to alter that position and investigate the effect of the centre of gravity location. The location of the centre of gravity was varied by 50 mm in two orthogonal directions (up-down and forward-back). This was considered a reasonable range of variations which were possible in reality. Both the lap and 3 point belt restrained surrogate FCS were examined.

### 8.10.1 THE LAP BELT RESTRAINED FCS

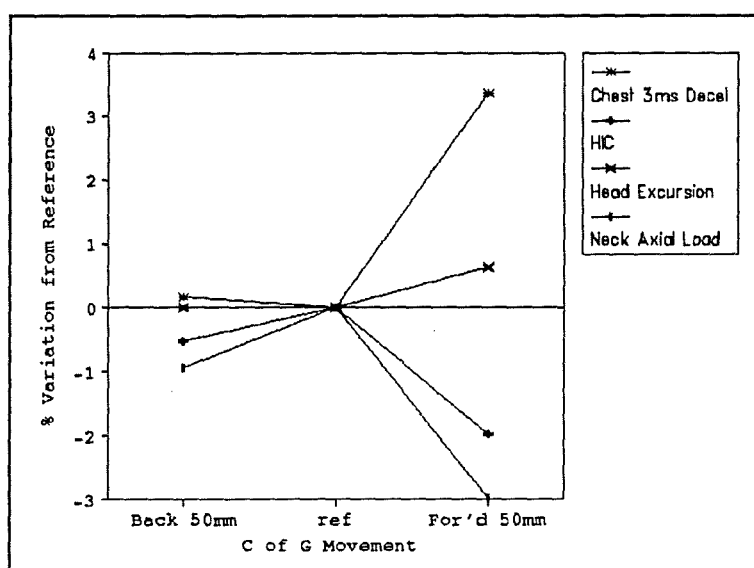
The results of the centre of gravity (CG) variation are shown in Figure 8.19 (vertical variation) and Figure 8.20 (horizontal variation). A horizontal movement was shown to have minimal effect with variations in the IPI of below 5%. A slightly greater effect was observed for a vertical movement. A lower CG position was shown to be preferable, as a reduction in all IPI was seen with the exception of chest 3ms deceleration (this was also observed for the shell position variation). Head excursion was shown to decrease as the CG position is moved downwards, this is



**Figure 8.19** Effect of a vertical variation of CG on a lap belt restrained FCS

due to slight reductions in FCS rotation. The lower CG position means that the moment of the dynamic mass about the point of rotation (approximately the lap belt) is reduced and therefore rotation is

reduced.



**Figure 8.20** Effect of a horizontal variation in CG of a lap belt restrained FCS

### **8.10.2 THE 3 POINT RESTRAINED FCS**

The vertical variation results are shown in Figure 8.21 and a similar plot for the horizontal variation is included as Figure 8.22. A horizontal movement in CG was shown to have negligible effect, whereas the vertical variation had a similar effect to that observed for the lap belt case. Head excursion decreased as the CG was moved down due to the decreased moment of the FCS mass. The reduction is only small in magnitude because the governing forces on the FCS are those of the occupant



(through the harness and seat contact), the restraining adult belt and the squab/set pan contact.

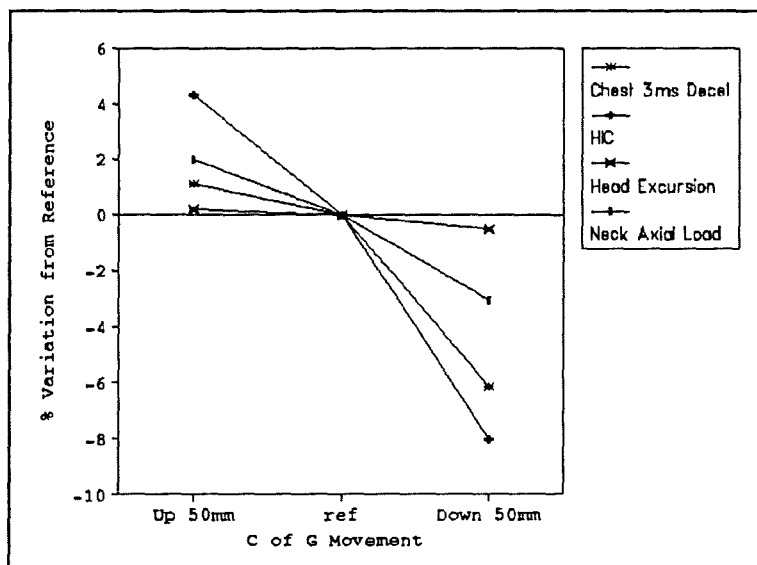


Figure 8.21 The effect of a vertical variation in CG on a 3 point restrained FCS

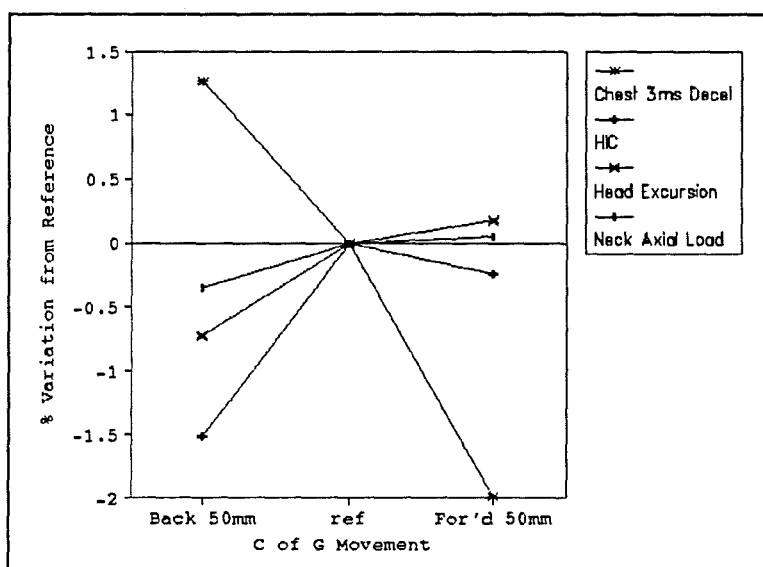


Figure 8.22 The effect of horizontal CG position on a 3 point restrained FCS

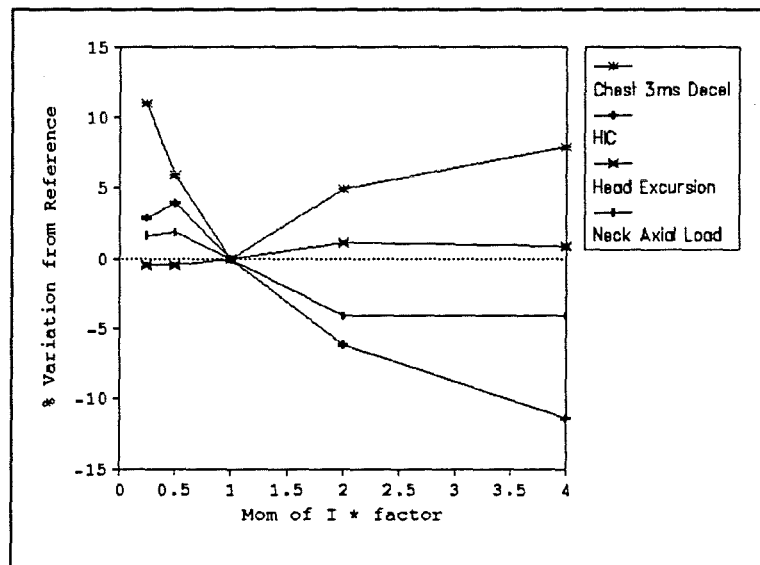
### 8.11 EFFECT OF FCS MOMENT OF INERTIA

The moment of inertia (MOI) of a FCS is not something that can easily be changed. It is of course defined by the geometry of the seat and it's mass distribution. However, with careful design the FCS moment of inertia could be arranged to conform to a given requirement. The MOI defines the rotational acceleration of the FCS and therefore the rotational position at a given time. Theory would suggest that if MOI was increased the angular displacement

of the seat would be reduced and therefore the occupant's head excursion would be reduced. In addition theory would imply that chest acceleration may be reduced. This part of the study was designed to investigate the possibilities of improving the occupant protection by a change in the MOI. A lap belt restrained FCS and a 3 point belt restrained FCS were considered.

#### 8.11.1 THE LAP BELT RESTRAINED FCS

The results of the MOI variation on a lap belt restrained FCS did not exhibit the expected outcome. Neither head excursion or chest deceleration decreased as MOI increased (see Figure 8.23). In fact the opposite result



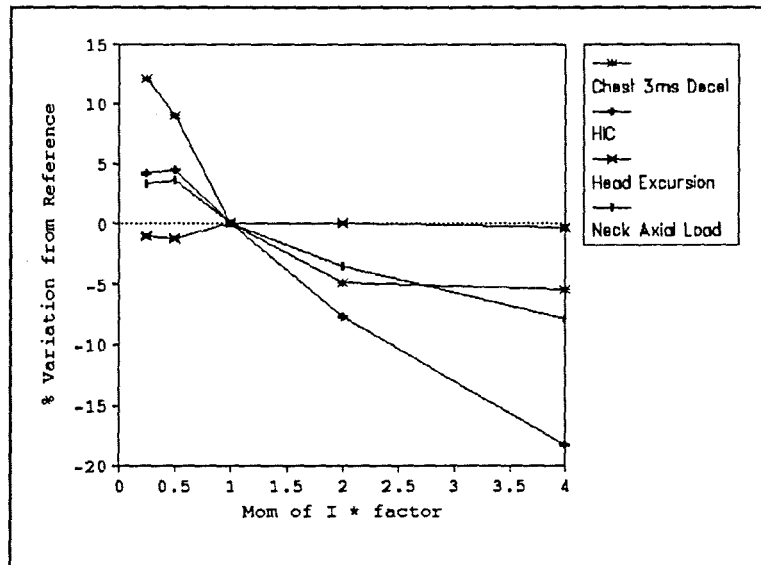
**Figure 8.23** Effect of moment of inertia variation on a lap belt restrained FCS

occurred. The increased moment of inertia causes a greater lag in the response of the FCS which causes the deceleration of the occupant to occur slightly later when the vehicle has decelerated more. The occupant therefore has a greater relative momentum to the vehicle and forces and displacements are therefore greater.

#### 8.11.2 THE 3 POINT RESTRAINED FCS

The 3 point restrained FCS results compare more favourably with the initial theory on the effect of the MOI change. All of the IPI (bar the head excursion which alters little) reduce as MOI increases (Figure 8.24). The positive effect of the MOI in this case compared with the lap belt restrained case is surprising,

because the FCS rotates less due to the upper anchorage strap. However the upper strap may reduce the response lag which was occurring with the lap belt but still allow the change in MOI to have an effect. The effect is



**Figure 8.24** The effect of FCS moment of inertia on a 3 point restrained FCS

relatively small (MOI increase 400% for 5% decrease in chest deceleration), thus the possibilities for using this parameter to govern FCS performance are minimal.

9 EXPERIMENTAL INVESTIGATION OF THE  
EFFECT OF VEHICLE PARAMETERS ON  
FRAMED CHILD SEAT PERFORMANCE

## 9 EXPERIMENTAL INVESTIGATION OF THE EFFECT OF VEHICLE PARAMETERS ON FRAMED CHILD SEAT PERFORMANCE

There were two possible methods available for the experimental investigation of the effect of vehicle parameters: 1) to use existing manufacturers car bodies; 2) to alter the ECE R 44 test seat. There were problems perceived with both these techniques.

If existing car bodies were used then some adaptation would be required for use on the RSEL test sled, but more critically there would be problems in identifying the effect of a particular variation in vehicle design. Each specific car design varies in many respects from the ECE R 44 test seat and therefore it would be difficult to determine the parameter governing the change in FCS performance.

If the second technique were adopted (alteration of the ECE R 44 test seat) a large amount of modification of the test seat would have been required. In effect a second test seat would have been required which was capable of variations such as belt anchorages, cushion depth and thickness. The construction of such a seat would have been possible but would have required significant cost and time.

Due to the difficulties with both of the possible experimental investigation methods it was decided that the MADYMO computer simulation would provide the most effective investigation technique. The use of computer simulation had on the whole been successful in the previous investigation of FCS design parameters (see last chapter) and was therefore considered an appropriate technique for the further work on vehicle parameters. The computer simulation work is presented in the next chapter.

In addition to the theoretical CVS work, it was considered useful to conduct some tests using the surrogate FCS installed in production vehicle bodies, which would help to quantify the possible changes in FCS performance in actual cars. Three rear halves of car bodies were obtained as a donation from TRL (all bodies were of cars manufactured in approximately 1986). The car bodies were stripped of all moving parts (driving gear, axles etc) and strengthened by the addition of struts in the B pillar position. They were then bolted onto an aluminium frame, which could then be bolted to the sled. The car bodies were given the three code numbers as follows;

HAC 1        Ford Sierra.

HAC 2a      Vauxhall Cavalier with split rear seat.

HAC 2b      Vauxhall Cavalier with full width rear seat.

Four tests were completed with each car body. The surrogate FCS was configured with a bar foot and the largest plate foot (see Section 7.3) for both anchorage methods (lap belt restrained or 3 point restrained). When the surrogate FCS was restrained with a lap belt it was placed in the centre rear position and secured using the existing belt anchorages. The 3 point restrained surrogate FCS was anchored with the cars existing inertia reel belt located in the offside rear position.

The lap belt restrained surrogate FCS was configured with the shell in position g (optimum for lap) and the 3 point restrained surrogate FCS was configured with shell position i. As in previous tests the dummy was instrumented with two triaxial accelerometers (one head one chest). Denton webbing load transducers were employed to measure loads in the adult belts and the CR harness. The results are shown in Table 9.i, together with the comparable ECE R44 test seat results.

**Table 9.i. Car body test results.**

Body Code or Test Seat	Adult Restraint <sup>#</sup>	CR Configuration		Results	
		Shell Pos.	Foot Type <sup>*</sup>	Chest 3ms Accel (g)	Head Exc (mm)
ECE R44	lap	g	bar	59.5	449
HAC 1	lap	g	bar	47.0	576
HAC 2a	lap	g	bar	41.0	541
HAC 2b	lap	g	bar	45.0	541
ECE R44	lap	g	plate	40.0	532
HAC 1	lap	g	plate	43.5	569
HAC 2a	lap	g	plate	45.5	528
HAC 2b	lap	g	plate	66.5	541
ECE R44	3 point	i	bar	54.5	548
HAC 1	3 point	i	bar	51.0	640
HAC 2a	3 point	i	bar	60.5	644
HAC 2b	3 point	i	bar	54.5	607
ECE R44	3 point	i	plate	53.0	529
HAC 1	3 point	i	plate	58.5	596
HAC 2a	3 point	i	plate	60.5	645
HAC 2b	3 point	i	plate	66.5	607

NOTE: Lap and 3 point restrained results are not directly comparable, due to the different shell positions used.

\* Foot size: bar = standard bar foot, plate = Largest 450x460mm plate foot.

# CR fitted in centre seat with lap belt, offside with 3 point belt.

It can be seen that in all bar one test the head excursions measured in a car body exceed those measured on the ECE R 44 test seat and in many cases exceed the 550 mm limit set in ECE R44. In the case of the bar foot configured, lap belt restrained FCS tested in car body HAC 1 the difference in head excursions is 127 mm. The reason for the large increases in excursion are largely due to difficulties in tightening the adult belts. During the test set ups it was noted that it was particularly difficult to tighten both the belt types in the car bodies. The lap belt was difficult to tighten because of poor accessibility, stiff seat squabs (which make it harder to push the FCS down) and the sculpturing of the squabs. Similar problems were encountered with

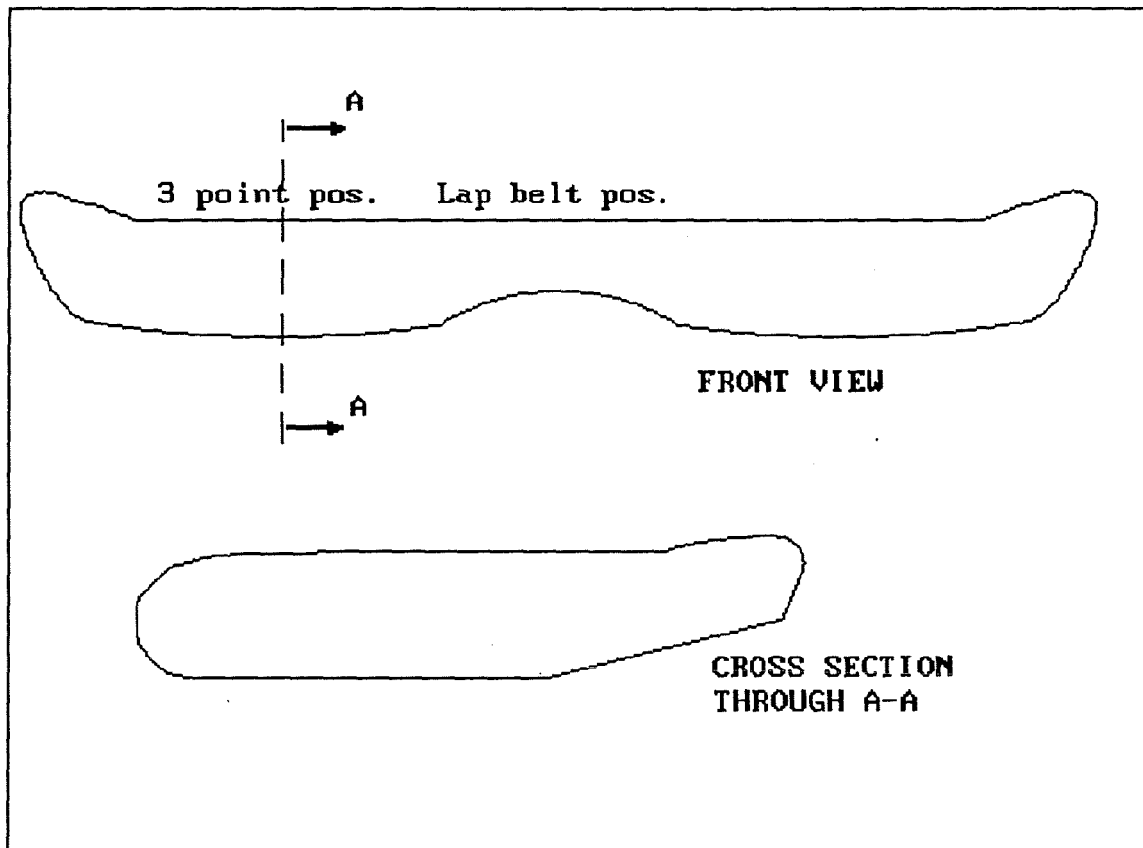
the inertia reel belt, but an additional problem was also encountered. The inertia reel belt cannot be tensioned in the same manner as a static belt because it can not be locked.

When the FCS was tested in a car body the addition of the largest plate foot did not appear to have a great effect on the performance of the FCS anchored with a lap belt. This is in contrast with the observation made on the ECE R44 seat tests [see Section 7.3], where the increase in foot size greatly decreased the chest acceleration and increased the head excursion. The lack of effect of the plate foot may be explained by the belt tensioning problems.

A comparison study of the two car bodies HAC 1 and HAC 2a, shows a greater head excursion in the latter body, when the CR is anchored with a 3 point belt. This is not the case with the lap belt restrained results or with the latter body configured with a full width seat (HAC 2b). The increase in excursion may be due to additional loading from the split rear seat in HAC 2a. The split rear seat can be seen to bend forward, during impact, on the high speed film.

Further conclusions are difficult to form from these results. The FCS was configured with a different shell position for the two restraint types. In addition the FCS was required to be in a different seating position for each adult restraint, which means a different squab thickness (see Figure 9.1). It is therefore not valid to compare the two sets of results. The most important feature of the results is the effect of adult belt tensioning and the difficulty in achieving a initial tight fitting. If an experienced researcher can not satisfactorily tighten the belts





**Figure 9.1** Sketch of typical car squab

in a car body with no doors or front seats, how can a parent be expected to achieve it in an actual whole car with a screaming child ?

There are many vehicle design parameters which have the potential to effect the performance of a framed child seat. Many of these have already been mentioned, namely:

- Adult belt anchorage position
- Belt adjustmenmt and inertia reel belt 'reel out'
- Adult belt stiffness
- Seat squab stiffness and shape
- Vehicle deceleration

The tests described above highlighted some limitations and problems with testing the effect of these parameters. Thus computer simulation was used to overcome these limitations. This work is described in the following chapter.

**10 COMPUTERISED INVESTIGATION OF THE  
EFFECT OF VEHICLE PARAMETERS ON  
FRAMED CHILD SEAT PERFORMANCE**

## 10 COMPUTERISED INVESTIGATION OF THE EFFECT OF VEHICLE PARAMETERS ON FRAMED CHILD SEAT PERFORMANCE

As discussed in the previous chapter MADYMO was chosen as the primary tool for the investigation of the effect of vehicle parameters on the framed child seat performance. The results of some experimental tests with actual car bodies are discussed in the last chapter. However the effects observed were thought to be mainly due to difficulties in anchoring the FCS with the adult belt, rather than the particular features of the cars' design (although the design of the vehicles' seats and belts were the reason for the difficulties in anchoring).

MADYMO crash victim simulation was used to investigate the effect of the following features of vehicle design:

- Adult belt anchorage positions
- Adult belt stiffness
- Seat squab stiffness
- Seat squab depth

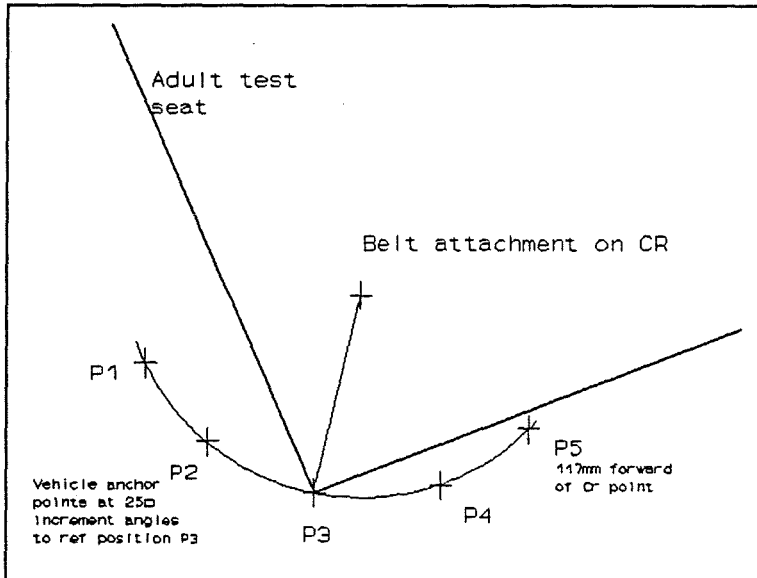
In addition the effect of slack in the diagonal section of a 3 point belt was examined in an attempt to support the 3 point belt (inertia reels) results observed in the car body tests.

The final section of the vehicle parameter investigation examined the effect of the vehicle deceleration pulse. The deceleration of the vehicle is defined by the object which is struck and the design of the vehicle. The latter could certainly be designed so as to alter the deceleration pulse for certain impact scenarios. In general the object which is struck can not be chosen in advance. But vehicles, motorway guardrails, sign posts and other roadside objects could be modified so as to improve the safety of an occupant of a striking vehicle. The work conducted in this

project was aimed at defining what features of the deceleration pulse define the severity of the child occupant response.

The six parameters which were examined are discussed in the following six sections.

### 10.1 ADULT BELT ANCHORAGE POSITIONS



**Figure 10.1** The five adult belt anchorage positions.

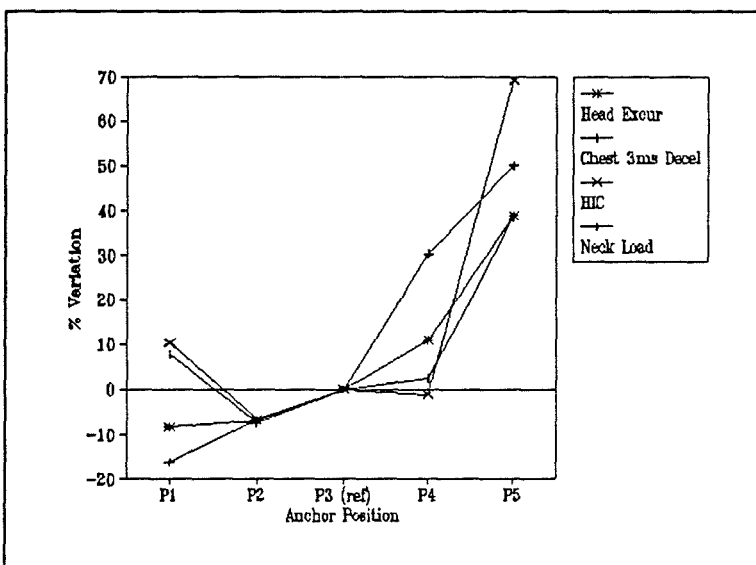
There is a tendency in modern vehicles towards more forward anchorage positions, in particular for the outboard lap anchorage position. The reason for this anchorage movement is to improve the protection for adult occupants using

the belt (by reducing submarining). However, it has been noted by child restraint users and fitters that the more forward anchorage causes difficulty in securing framed child seats. Therefore this part of the project examined the effect of five anchorage positions, on the impact performance of both a lap belt restrained FCS and a 3 point restrained FCS. The five anchorage positions that were used are shown in Figure 10.1. The standard position was taken as the CR point on the adult test seat (see Figure 5.1), as this is where the lap belt passes between the two seat sections (back and squab). Both anchorage positions were moved for the lap belt restrained FCS simulations, whereas only the outboard lap anchorage was moved in the 3 point restrained FCS simulations. The choice of 3 point anchorage movement was

considered to reflect the anchorage conditions in modern vehicles.

The lap belt restrained and 3 point belt restrained results are presented separately in the following two sections. They are not directly comparable as the model was configured with different shell positions. The lap belt simulations are configured with shell position g and the 3 point with shell position i (the optimum positions. See Section 8.2).

#### 10.1.1 THE LAP BELT RESTRAINED RESULTS



**Figure 10.2** Lap belt restrained FCS, result of a movement of anchorage positions.

The results of the lap belt restrained FCS simulations are shown in Figure 10.2. The head excursion and the chest deceleration are seen to rise as the anchorage positions are moved to the more forward (higher numbered) positions.

The head excursions are increased because the FCS moves a greater distance. This is because the adult belt must rotate to a horizontal position before it can restrain the FCS, and as the anchorage is moved forward the FCS must move further forward to achieve this. The decelerations are increased due to the actual deceleration process beginning at a later time (when the FCS is moving forward and the belt straightening the occupant is in 'free-flight' ie; not decelerating). The vehicle is therefore nearer to its final resting position, and the child has a reduced

distance to decelerate within (total restraining distance is occupant movement plus vehicle movement during deceleration). Also the portion of the vehicle-occupant relative movement that occurs due to free-flight is increased relative to the portion during deceleration. Thus although the excursions are increasing the actual distance moved during deceleration is reduced.

### 10.1.2 THE 3 POINT RESTRAINED RESULTS

The 3 point restrained results show a similar pattern to the lap belt restrained results (Figure 10.3). Although because only one of the lap anchorages is moved, the effect on the dummy response is not so great. However the

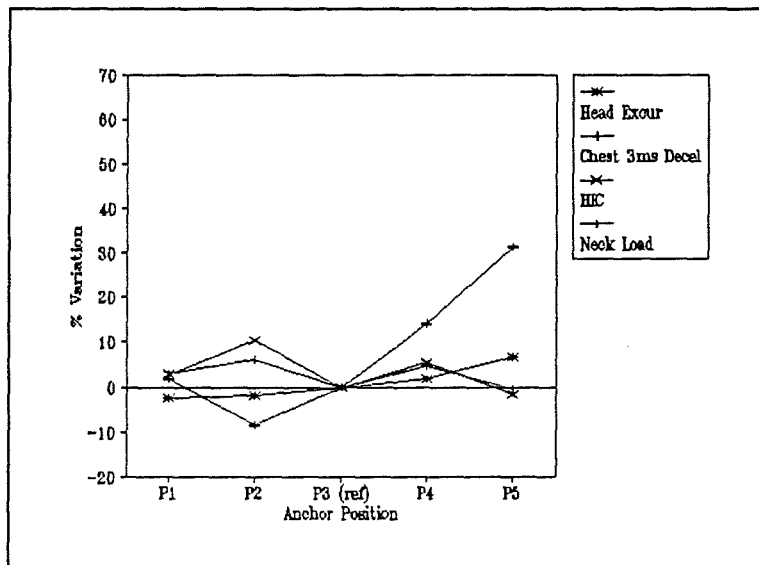


Figure 10.3 3 point restrained FCS, result of a movement of anchorage positions

chest deceleration is increased by approximately 30 % and the 7% (approx 40mm) increase in head excursion would increase the probability of a head impact.

### 10.2 ADULT BELT STIFFNESS

The stiffness of the adult belt which is used to anchor the FCS is totally governed by the requirements for restraining adults. However, it was felt appropriate to assess the effect of the webbing stiffness on the FCS so that any future belt design could include the requirements for child restraint anchoring. The force-extension curves defined for the adult belt webbing in the MADYMO model were scaled by the factors: 0.25, 0.5, 2 and 4. Thus

the range of webbing stiffness was from -75 to +400% of the standard belt. As before both a lap belt restrained and a 3 point restrained FCS were considered.

#### 10.2.1 THE LAP BELT RESTRAINED RESULTS

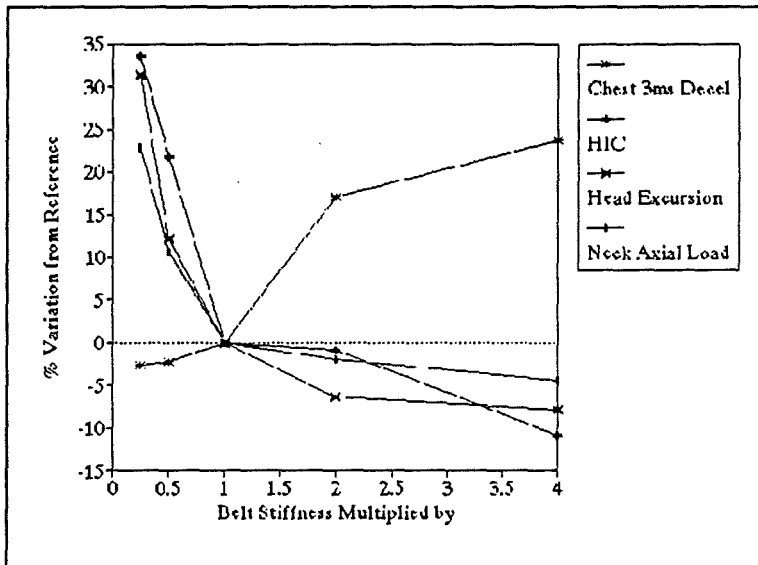


Figure 10.4 The effect of adult webbing stiffness on a lap belt restrained FCS

The effect of the changes to lap belt stiffness on the injury potential indicators are shown in Figure 10.4. As we would expect, when stiffness was increased the head excursion was reduced and the relationship

between the two appears to be of an inverse square form.

The form of the relationship can be explained by considering the energy transformations as the deceleration occurs. If we equate the maximum kinetic energy (just before impact) and the maximum strain energy in the webbing we can gain an expression for the relationship between webbing stiffness and extension (see Equation 10.1). The changes in webbing extension will be directly translated to changes in occupant motion, and thus an inverse square relationship is observed.

$$SE \propto KE \Rightarrow \frac{1}{2} Kx^2 \propto \frac{1}{2} mv^2$$

$$\therefore x \propto \sqrt{\frac{m}{K}}$$

Equation 10.1 Relationship between webbing extension (x) and webbing stiffness (K)

Although the head excursion to belt stiffness relationship appears to vary in form in accordance to basic theory, the magnitude of the variation does not. For example for a reduction in stiffness of 50 % we might have expected a 40 % increase in the head excursion, but the actual increase was approximately 11 %. This is due to the influence of the many other factors governing the extent of movement of the occupant. These factors include the restraint due to the seat squab and pan and features such as FCS rotation, occupant rotation and belt slack.

The occupant deceleration also varies in a logical manner. As stiffness is increased the 3 ms chest deceleration is shown to increase with stiffness. The higher stiffness belt which induces lower occupant movement will also apply greater forces which increase the acceleration of the occupant.

The reason for the decrease in HIC and neck load as belt stiffness is increased is not clear. The dynamics of the problem are complicated and it would have required considerable effort to investigate this feature of the results. As little benefit could be perceived in changing adult belt design it was decided not to pursue the explanation further.

#### 10.2.2 THE 3 POINT RESTRAINED RESULTS

The results for the 3 point restrained FCS are shown in Figure 10.5. As in the lap belt restrained case there is an apparent inverse square relationship between belt stiffness and head excursion. The magnitude of the variations in head excursion are also similar to that observed for the lap belt restrained case.



The chest 3 ms deceleration also behaves in a similar manner to that observed previously, except that the deceleration increases when the belt stiffness is reduced to its lowest level (0.25). The 3 point

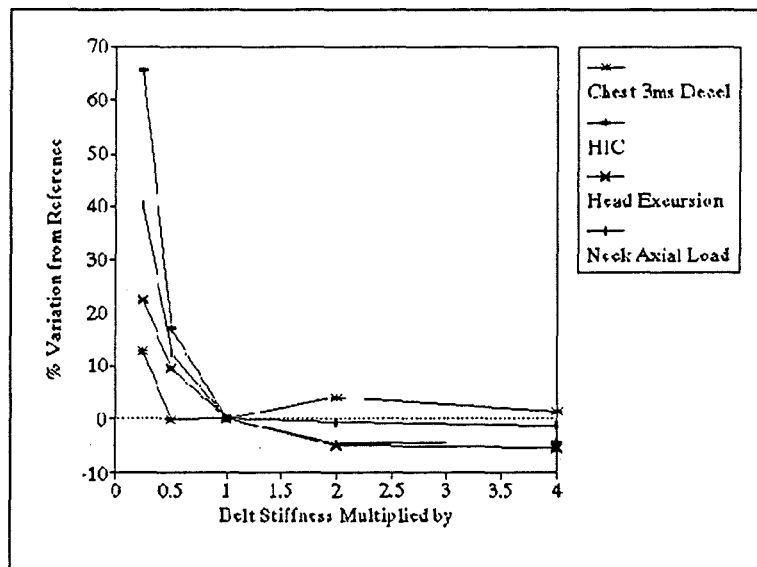


Figure 10.5 The effect of 3 point webbing stiffness on a FCS

restrained FCS is generally almost entirely anchored by the adult belt (unlike the lap belt restrained case in which the seat pan plays a major role). However, when the belt stiffness is reduced and greater FCS movement occurs the seat pan loads the FCS and causes greater chest decelerations.

Both the lap belt and 3 point belt restrained results appear to show that little benefit could be gained from a change in adult belt stiffness. Any reductions in chest deceleration which could be effected are offset by much greater changes in head excursion. As head impact is the major cause of serious injury of child vehicle occupants, this increase in head excursion would not be acceptable. It should be noted that changes in adult belt webbing stiffness would be unlikely in any event.

### 10.3 ADULT SEAT SQUAB STIFFNESS

There is some variation in the stiffness of seat squab material used in vehicles. Sports cars and sportier models of the modern family car tend to have stiffer "bucket" type seats, whereas the more common models have softer seats installed. The FCS partially

relies on the seat squab for its anchorage and it was therefore considered important to investigate the effect of the squab stiffness on the performance. The variation in squab stiffness was modelled by multiplying the force-penetration characteristic which was defined for the squab-FCS foot contact by the following factors; 0.25, 0.5, 2 and 4.

Differences on the effect of FCS foot size had been observed between the lap belt and 3 point belt restrained FCS tests (Section Figure 7.3). This was thought due to the variation in importance of the seat in the restraint of the two cases. It was therefore considered likely that differences would be apparent if the squab stiffness was varied and thus both anchorage methods were considered.

#### 10.3.1 THE LAP BELT RESTRAINED RESULTS

The minimal effect of the changes to the squab stiffness are shown in Figure 10.6. A reduction in squab stiffness of 75 % increased chest 3 ms deceleration by approximately 8 % whilst head excursion remained almost

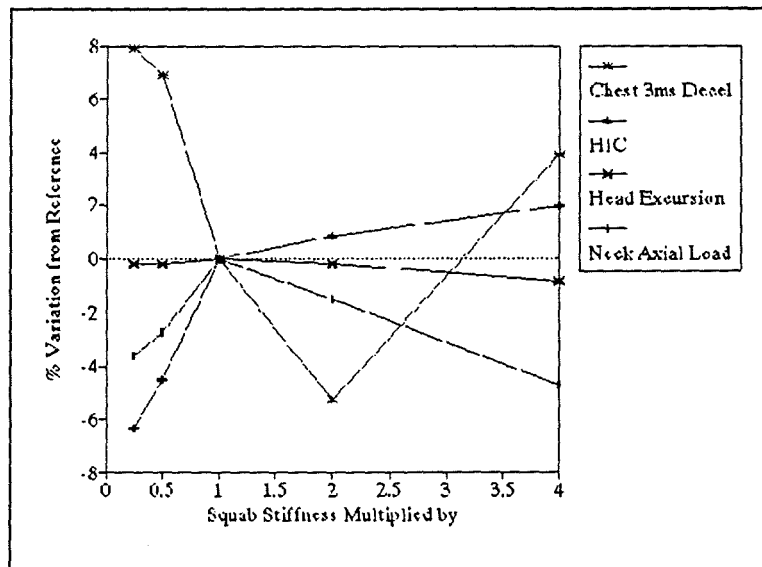


Figure 10.6 Effect of squab stiffness on a lap belt restrained FCS

constant. An increase in squab stiffness by 400 % yielded similar results, with the chest 3 ms deceleration varying rather erratically. These results illustrate the minor role played by the squab in the anchorage of the FCS. The main anchorage

supplied by the seat is via the seat pan when the squab is totally crushed.

There was no obvious explanation for the erratic variation in chest deceleration. Reruns of the models were conducted to check for error, but none was found. If a larger number of computer runs were conducted with a larger amount of data output then it may of been possible to identify the cause. However, since the squab stiffness was found to have a relatively minor effect on FCS performance, this was not explored further.

#### 10.3.2 THE 3 POINT RESTRAINED RESULTS

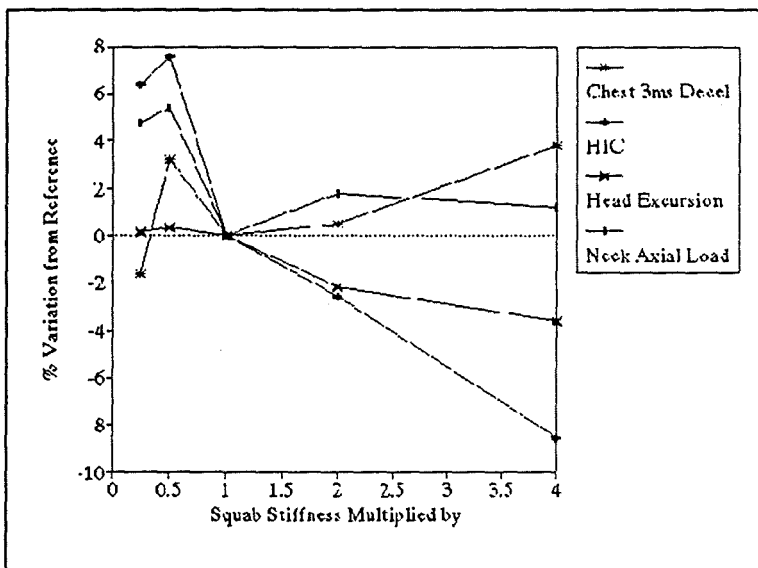


Figure 10.7 The effect of squab stiffness on a 3 point restrained FCS

The results gained for the 3 point restrained FCS were less erratic and more significant than the lap belt restrained case. With a 400 % increase in squab stiffness the head excursion was reduced by 4 % with a similar increase in

chest acceleration. It was already hypothesised from the experimental work on foot size that the 3 point restrained FCS was mainly anchored by the belt itself. And the small variations observed in these results supported this theory. The variations were more consistent than in the lap belt case because the 3 point restrained FCS does not 'bottom out' on the seat pan as in the former case. Thus the effect of the squab stiffness is more clear.

The small variation in IPI yielded from a large stiffness changes mean that there should be little concern over the effect of seat squab stiffness in actual production vehicles.

#### 10.4 ADULT SEAT SQUAB DEPTH

The experimental examination of the effect of foot size together with the CVS results presented in the previous section suggested that the squab stiffness does not have a great affect on the FCS performance. The differences observed in the experimental foot size results were thought to be due to the differences in effective squab depth and other factors such as energy absorption in the structure. It was therefore important to investigate the effect of squab depth.

The squab depth that is under a FCS in a vehicle will vary between different vehicles and seats in a given vehicle. Figure 9.1 in the last chapter is a sketch of a typical rear seat squab and shows the different thicknesses

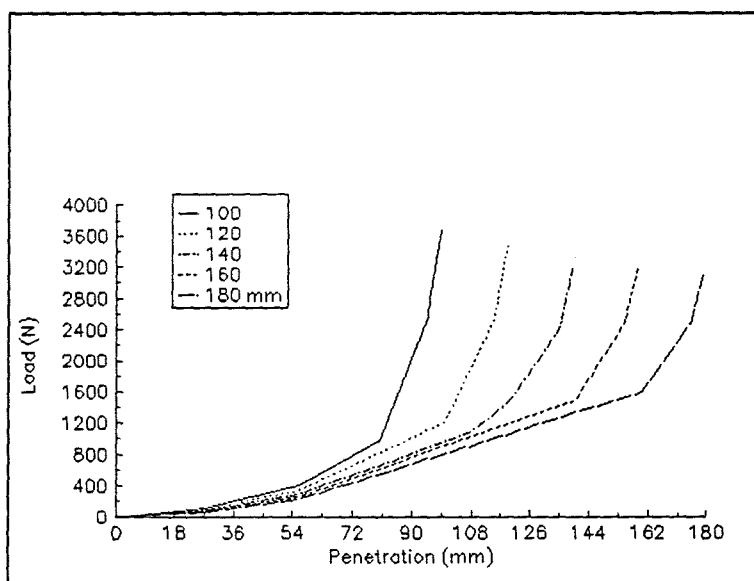


Figure 10.8 Assumed squab contact force change with depth

through the cross section. The fact that squab thickness can vary dramatically from the standard 140 mm of the ECE R44 test seat shows the need to quantify the effect of this parameter.

The effect of a variation in the seat squab depth was examined using the existing model. Depth was varied by vertically moving

the plane representing the seat pan in two 20 mm increments up and down. Thus five squab thicknesses were considered; 100, 120, 140, 160 and 180 mm.

The squab material was assumed to be the same for all simulations, therefore the stiffness of the squab-FCS foot contact interaction had to be adjusted accordingly. The overall squab stiffness was assumed to vary in a similar manner to that of a spring; ie inversely with thickness of cushion material. Thus the squab-FCS foot contact interaction curve measured for the 140 mm thick squab was scaled as follows;

$$K_{new} = K_{140} * \frac{140}{thickness}$$

The effect of the thickness of the squab was also considered in terms of bottoming out on the hard seat pan. Figure 10.8 shows the resulting contact force curves used in the models.

#### 10.4.1 THE LAP BELT RESTRAINED FCS RESULTS

The effect of this variation on the dummy response is shown in Figure 10.9. Head excursion is shown to increase as squab depth is increased.

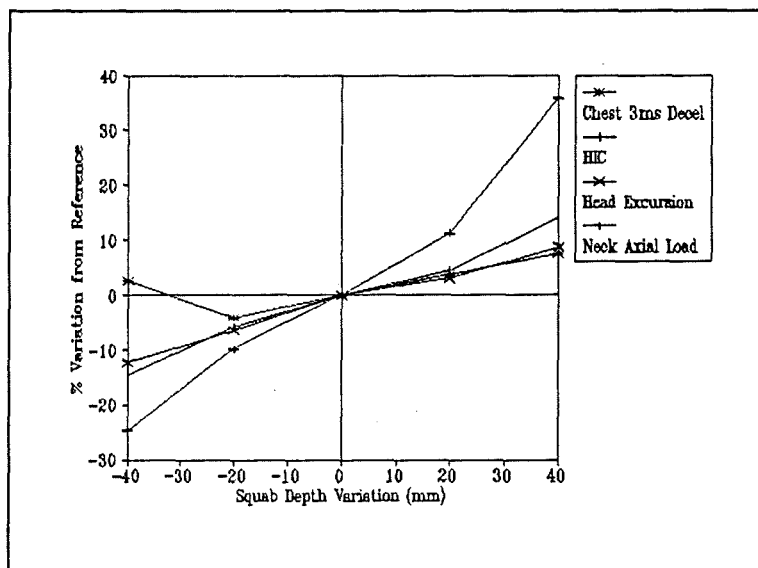


Figure 10.9 Squab depth effect on lap belt restrained FCS

This was an expected result, as greater

squab depth allows greater FCS movement. In addition there was a general increase in chest deceleration which was due to similar reasons as observed in previous parts of the investigation where

a less well restrained occupant was considered. ie; the occupant undergoes a longer period of free-flight and is thus decelerated at a later point in the vehicle's deceleration pulse. Thus the occupant's deceleration is increased.

#### 10.4.2 THE 3 POINT BELT RESTRAINED FCS RESULTS

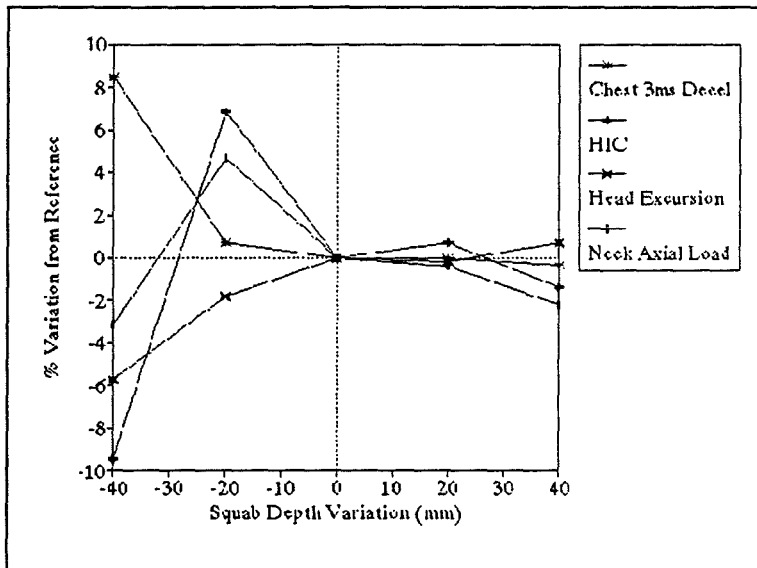


Figure 10.10 Effect of squab depth on a 3 point restrained FCS

The 3 point restrained results exhibited similar characteristics to those of the lap belt restrained case, but of lesser magnitude (see Figure 10.10).

The extra upper anchorage supplied by the shoulder belt, restricts the FCS rotation and means that the FCS is less reliant upon the adult seat for constraint. Thus the squab depth variation would be expected to have a lesser effect.

As observed with the previous restraint method, the requirements of a FCS appear to be a thin (or non existent) seat squab. A thin squab allows the FCS to quickly depress the cushion and reach the solid seat pan. When this occurs the FCS is more rigidly anchored and can decelerate with the vehicle.

#### 10.5 THE EFFECT OF SLACK IN THE DIAGONAL OF A 3 POINT BELT

It has already been shown in this document and others that slack in the harness of a child seat has an adverse affect on the

performance of the seat. The same adverse effect would be expected when slack is introduced into the anchorage straps restraining the child seat. The simulations presented in this

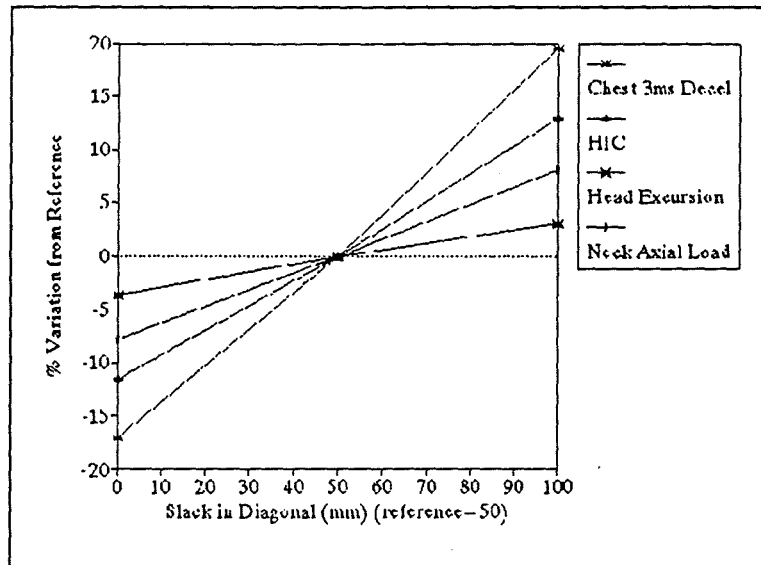


Figure 10.11 Effect of slack in the diagonal of a 3 point belt when were not conducted to restraining a FCS

support this theory. The vehicle body tests which are discussed in the previous chapter showed a large difference between the performance of a FCS when tested in a ECE R44 test seat and when tested in a vehicle body. In particular the head excursions measured in the car body tests were significantly greater than in the test seat. One of the factors which was thought to contribute to this difference was the reel out from the spool of the adult inertia reel belt and the initial lack of tension. The inertia reel belt was found to be difficult to adjust to yield a satisfactory tight anchorage.

All the tests conducted on the ECE R44 seat and those previously simulated, used a static belt with 50 mm of slack introduced in the diagonal section. The idea behind the introduced slack was to simulate reel out from a typical inertia reel belt. However, it has been observed in some tests that reel out can be considerably larger than this amount. This section of the thesis attempted to identify the effect of the reel out. Two extra simulations were conducted, one with no slack and one with 100 mm (double) slack.

The results are shown in Figure 10.11. A linear relationship can be observed in these results. All of the IPI increased with diagonal slack, however the increase in head excursion was only 17 mm (5 %). Thus the increases in head excursion observed in the vehicle body tests can not be solely attributed to diagonal belt slack.

The 3 point belt model used in these simulations did not allow slip between the diagonal belt and the lap belt. This assumption was not considered to be likely to affect the results to any great extent.

#### 10.6 VARIATION OF INPUT DECELERATION PULSE

The deceleration pulse that is imposed on the occupant of a vehicle is dependant upon the vehicle's design. Lundell(1984) examined the effect of the crash pulse on the belted adult occupant in 1984. The author can find no work which

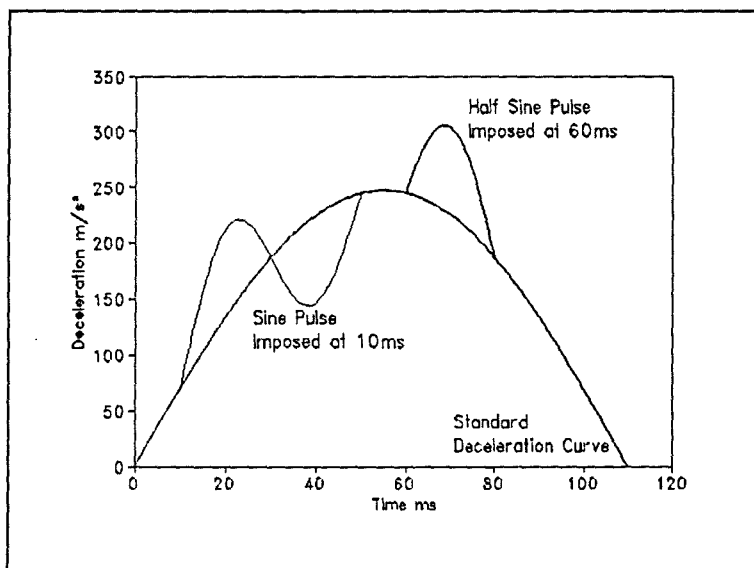


Figure 10.12 Diagram showing standard deceleration pulse with additional sine and half sine pulses.

examines the effect on a restrained child. It would be unfortunate if the requirements for optimised adult occupant protection and testing were different for the restrained child. With this in mind it was decided to reproduce the work of Lundell, but replace the lap belt restrained adult occupant with a child occupant restrained in a FCS.



The investigation comprised the imposition of an secondary imposed deceleration pulse on a main standard pulse. The standard pulse was a half sine pulse of amplitude  $247.7 \text{ m/s}^2$  and half period 110 ms. This pulse roughly approximated the typical pulse in a ECE R44 test.

The secondary pulse was either a full one cycle or a half cycle sine wave. The amplitude of the imposed wave was defined by velocity amplitude not deceleration. Figure 10.12 shows examples of the imposed additional accelerations. Both the time of application and the velocity amplitude was varied, for both full sine and half sine imposed variations. The full sine additional pulse imparts a local variation in the velocity that does not alter the total vehicle velocity change. The half sine additional pulse imparts an alteration of the total velocity change. Refer to Lundell(1984) for a fuller explanation. The period of the additional imposed pulse is 40ms in all cases.

Only the lap belt restrained FCS was considered. It was not thought likely that the 3 point restrained case would exhibit radically different results. In total 25 simulations were conducted for this part of the investigation. The results of the vehicle deceleration variations are shown in Figure 10.13.

It can be seen that the dummy response is more sensitive to a total velocity change (half sine) than to a local velocity change (sine). That is the results on the right side of Figure 10.13 are more spread than those on the left. This is not surprising as increases in total velocity change are also increases in energy change.

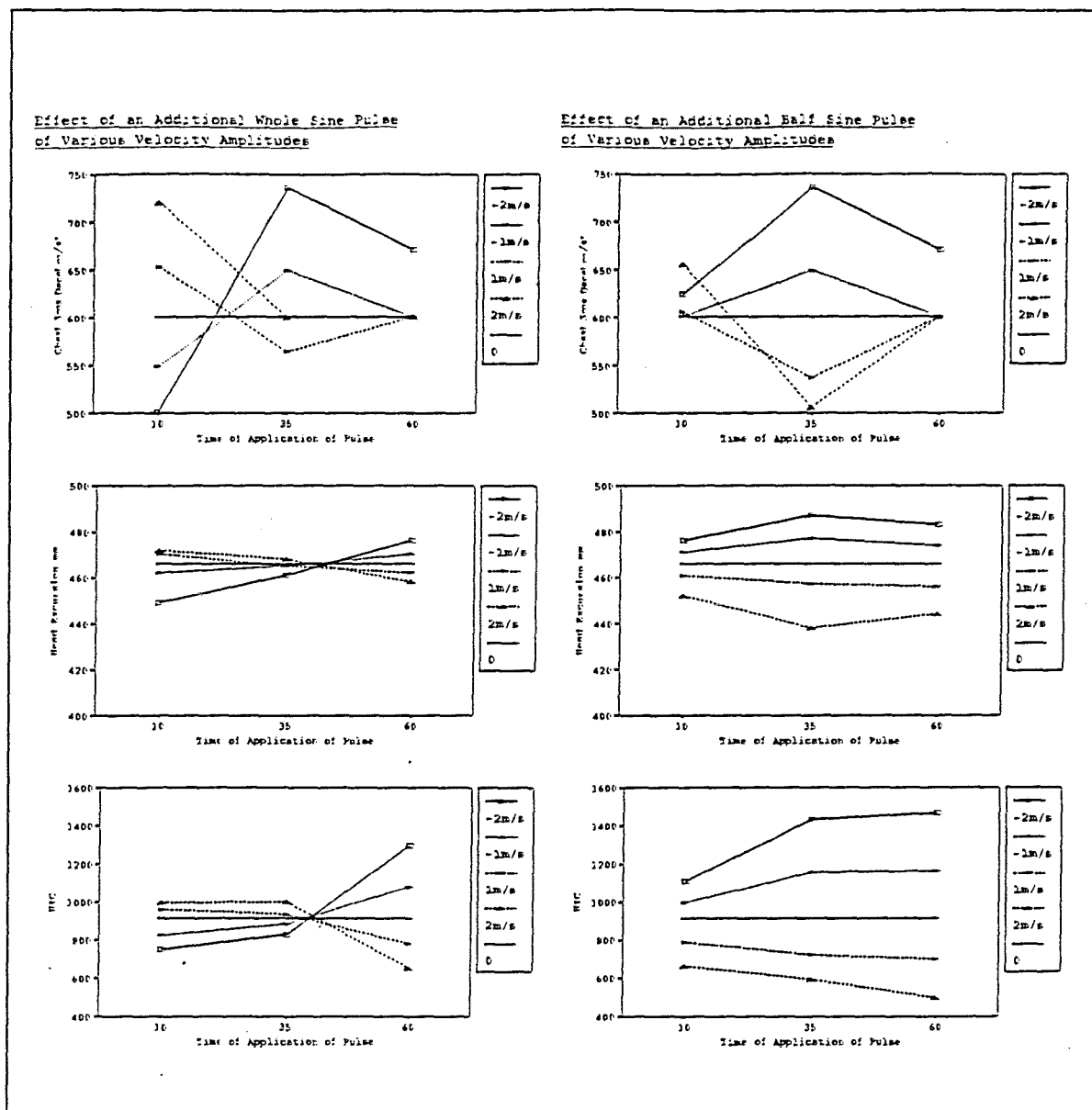


Figure 10.13 Effect of changes in vehicle deceleration pulse

The half sine results suggest that the occupant response is more sensitive to an imposed acceleration the later the application time. Whereas the dummy response for a whole sine added pulse could be considered optimised (least effect) for a time of application of approximately 35ms. In either case large deceleration pulses at the latter stages of vehicle deceleration should be avoided. The later pulses have a greater effect because the occupant is in a more forward position and belts are tensioned. There is therefore a more direct load path between occupant and vehicle and thus variations in the vehicle's deceleration are easily transmitted to the occupant. If the

occupant is in the period of free flight there is a buffer between the vehicle and occupant.

These results are in agreement with those of Lundell (the restrained adult case). Thus unlike the positioning of the adult lap belt there is no conflict between the safety requirements for children in FCS and adults.

11 INVESTIGATION OF THE EFFECT OF SOME  
PARAMETERS ON THE INJURY POTENTIAL  
TO THE CHILD HEAD AND NECK

## 11 INVESTIGATION OF THE EFFECT OF SOME PARAMETERS ON THE INJURY POTENTIAL TO THE CHILD HEAD AND NECK

All of the previous parts of this project have only dealt with head and neck injury in terms of reducing the risk of head and neck impact. This chapter of the thesis documents the work that has been concerned with the investigation of non impact head and neck injuries. This work has been conducted solely by use of the MADYMO3D crash victim simulation package, no appropriate crash tests could be conducted with the hardware that was available (there was no capability in the TNO P3 dummy for the measurement of neck loads).

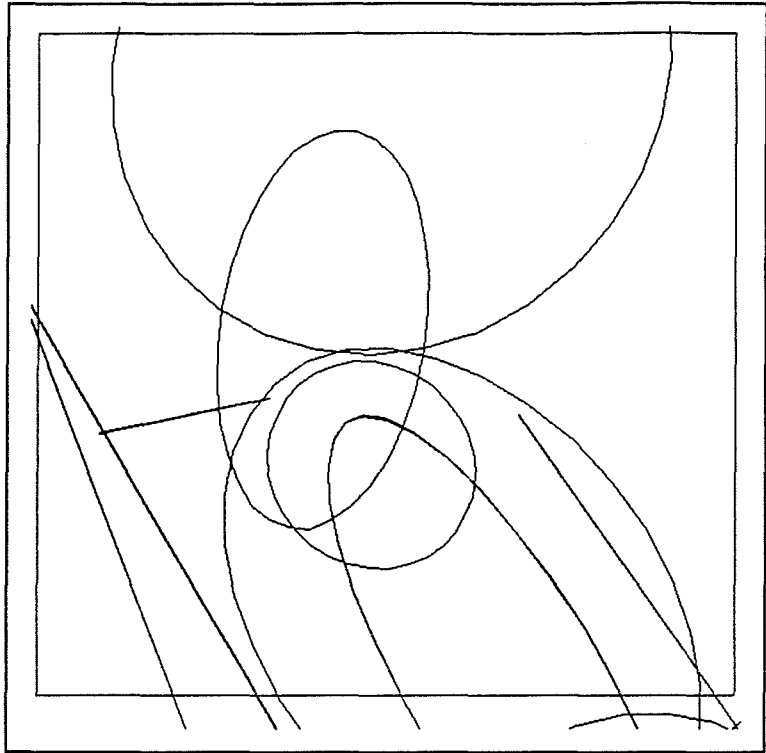
The first thing that will be discussed in this chapter is the development of the improved TNO P3 MADYMO3D representation neck. The chapter will then be continued with the presentation of the work that has been conducted with the improved neck.

### 11.1 IMPROVING THE REPRESENTATION OF THE DUMMY NECK IN MADYMO

The neck as represented in the MADYMO3D TNO database supplied with the software is a single rigid element with a joint at each end, it does not flex and bend as the actual dummy neck. Because of this major difference in the structure of the MADYMO3D TNO neck, it was not considered appropriate to use the model in neck injury investigation. This lack of confidence in the model to dummy fidelity is shown later to be justified.

The dummy neck is a little like a human neck in its construction (see Figure 11.2). The dummy neck comprises 6 rigid polyamide core elements (representing the cervical column), surrounded by flexible polyurethane outer rings (representing muscle tissue). Tension in the neck is resisted by a central steel cable which

runs the length of the neck and torso of the dummy. The steel cable represents the ligaments in the cervical column together with the other muscle components working in tension. This total structure, like the human neck, is a system of several joints which allow



**Figure 11.1** Standard MADYMO neck representation as supplied with the MADYMO database

bending and some lateral movement. This is not represented in the standard TNO P3 database. The neck as shown in Figure 11.1 comprises a single non flexible element with only two joints.

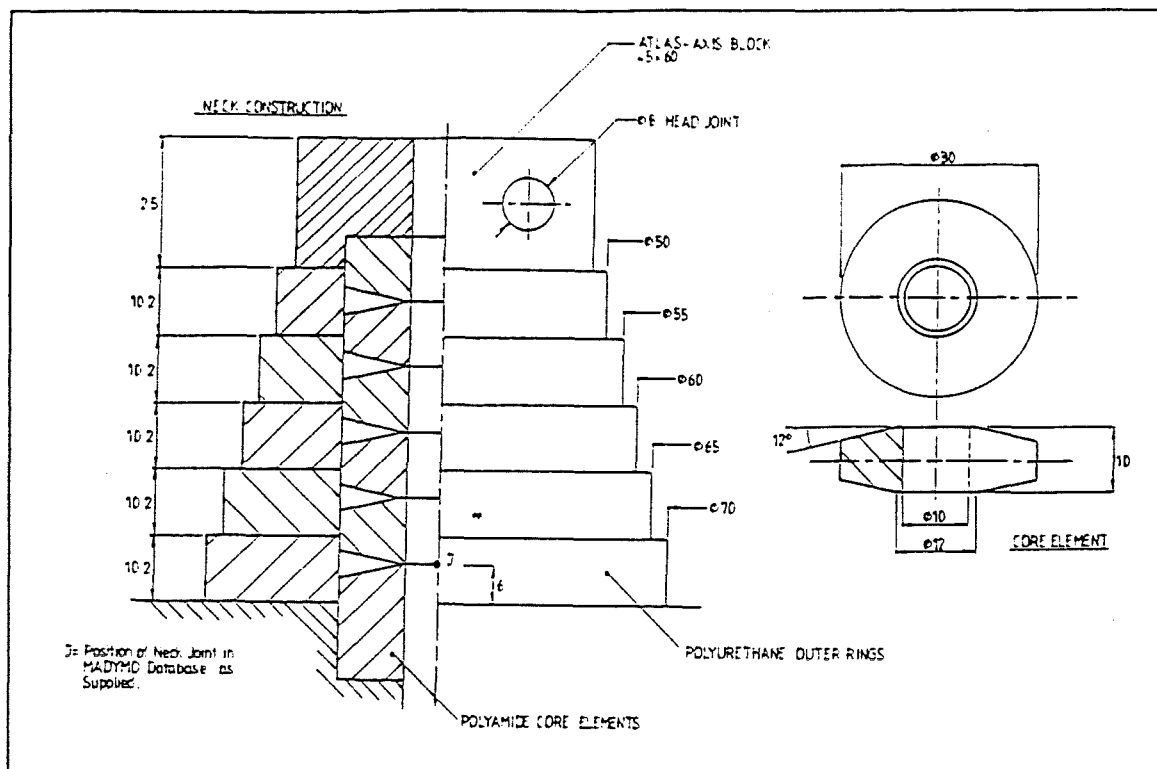


Figure 11.2 Drawing of the TNO P3 Dummy neck construction

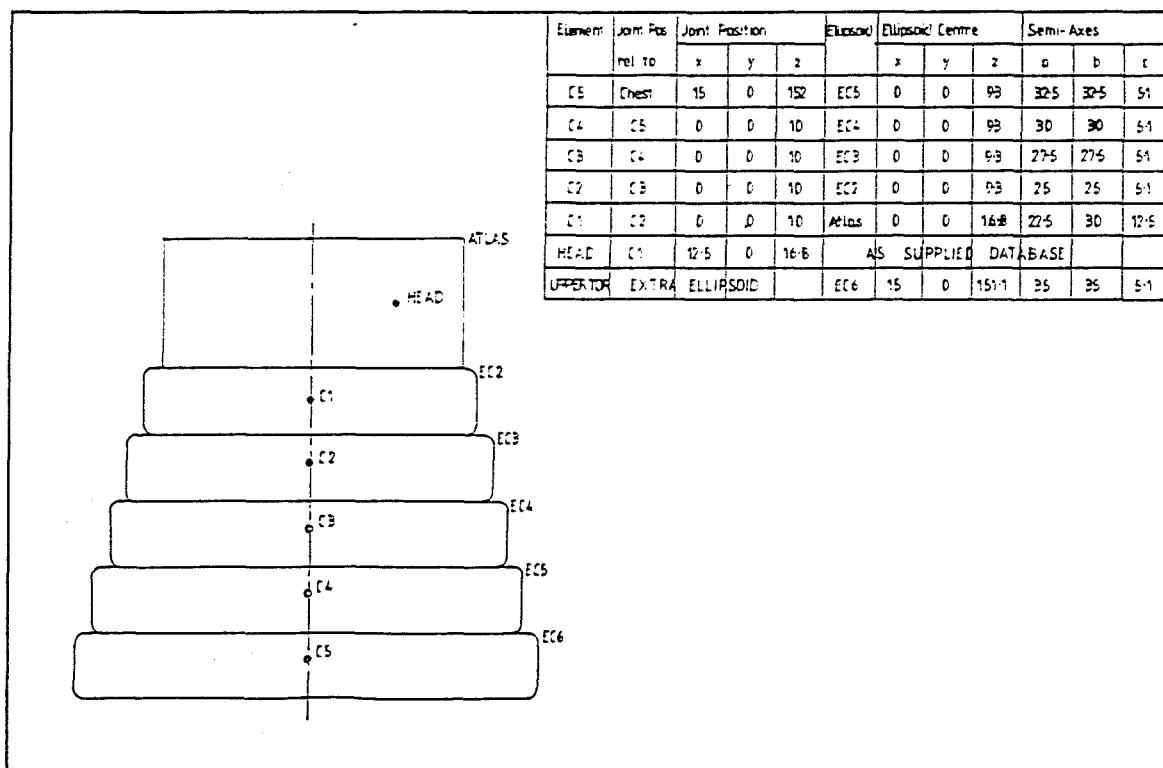


Figure 11.3 Spatial layout of the improved P3 MADYMO neck model

Thus it was decided that it was necessary to improve the representation of the dummy neck in the MADYMO3D model, i.e. to make it more dummy-like rather than human-like. To this end it was necessary to create a neck model that was composed of a series of joints, which were designed to represent the structure of the dummy neck.

The new neck model comprised 5 elements linked by six joints (see Figure 11.3). The joints are located at the interfaces of the rigid central core elements of the actual dummy neck. These points are the fulcrums for bending in the dummy neck.

Attached to each MADYMO3D element is an ellipsoid of dimension equal to the polyurethane outer rings of the dummy. These ellipsoids were assigned a high order, thus making them more rectangular (see section 2.3.1). The rectangular ellipsoid was the closest approximation to the actual dummy neck outer ring shape that was possible with MADYMO3D.

Each element in the neck construction required a mass and mass moment of inertia to be defined. The existing mass of the P3 database neck was divided into 5 values which were in proportion to the volume of each neck ring. The moments of inertia were considered small, the existing database value was 0.001 Kg/m<sup>2</sup>

There were three choices for the method of defining the stiffness characteristics of the new neck model.

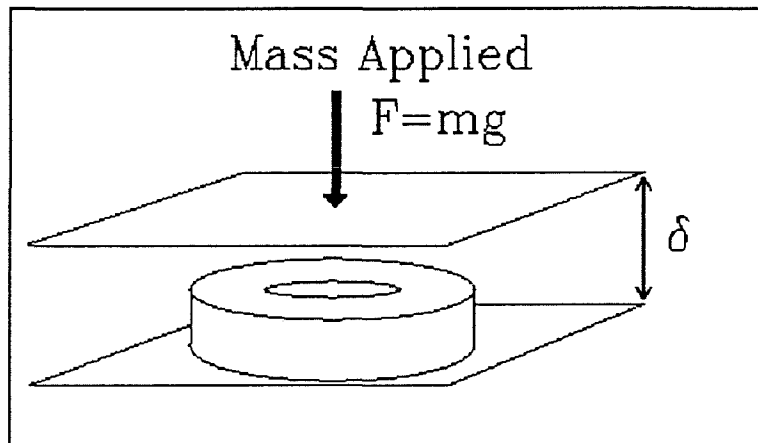
- 1) Purely by joint characteristics
- 2) Purely by force - penetration characteristics of the neck ring ellipsoids
- 3) A combination of the above two cases

It was decided that the last method would be an unnecessary



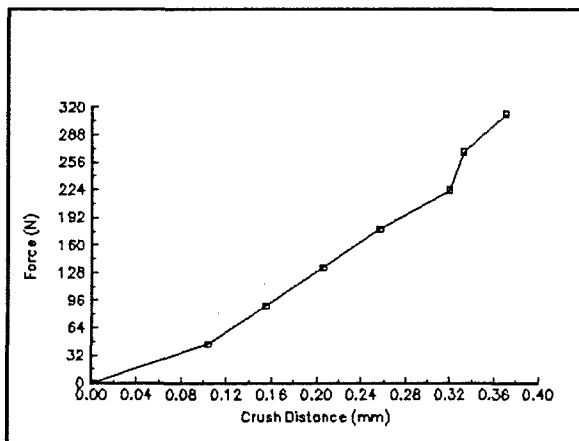
complication of the model, in that it would require two sets of stiffness data for each neck element. Initially it was decided that the second method would provide the most realistic stiffness characteristic for the neck, as this would operate in a similar manner to the actual dummy neck. The P3 database which included the improved neck model, with the neck stiffness characteristics defined by method (2) above was designated P3MRDI.

In order to define the contacts between the neck elements it was necessary to measure the stiffness of the dummy neck polyurethane outer rings. This was

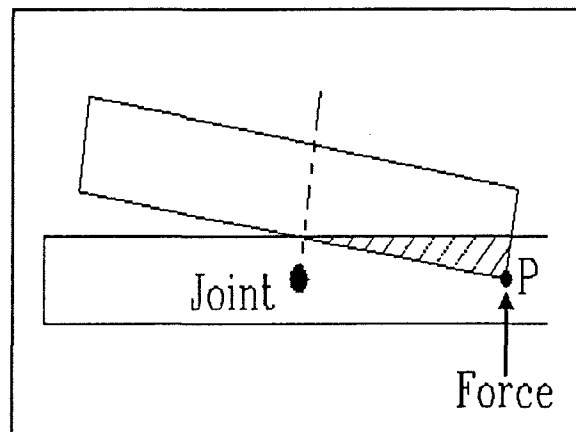


**Figure 11.4** Test procedure for neck polyurethane outer rings

conducted by a simple experiment (see Figure 11.4). The neck rings were loaded in a vertical direction using known masses. The deflection of the ring was then measured with a dial gauge. The results of this experiment are shown in Figure 11.5



**Figure 11.5** Results of Neck Polyurethane Outer Ring stiffness test



**Figure 11.6** Penetration force as calculated in MADYMO. Shaded area shows actual penetration

The force that was measured for the ring was then adjusted to account for various factors. Firstly the force was adjusted for each size of neck ring. It was assumed that the stiffness of each ring was proportional to the area and the forces were adjusted accordingly. The other adjustments were made to account for the manner that MADYMO3D calculates such contact interactions. Figure 11.6 shows two neck ellipsoids when the neck is under load. The force that is applied in a MADYMO3D contact interaction is taken from a user defined penetration-force characteristic. MADYMO3D calculates the depth of the deepest penetration (point P) and then applies the given force to this point. It can be easily observed from the diagram that the actual average penetration depth is one half of the maximum penetration. The area of penetration is also one half of the area of crush in the experiment discussed above. In addition MADYMO3D applies this force at the maximum distance from the joint. Logic tells us that the average force should be applied half way between the joint and point P, if the moment of the force about the joint is to be correct. Thus the adjustment for these three factors should be  $1/2 \times 1/2 \times 1/2 = 1/8$ . Therefore the force measured in the experiment above was divided by 8.

In order to develop and validate the new neck model it was necessary to gain a measurement of the dynamic response of the actual dummy neck. This process will be discussed in the next section. The further development of the model will then be discussed in the following section.

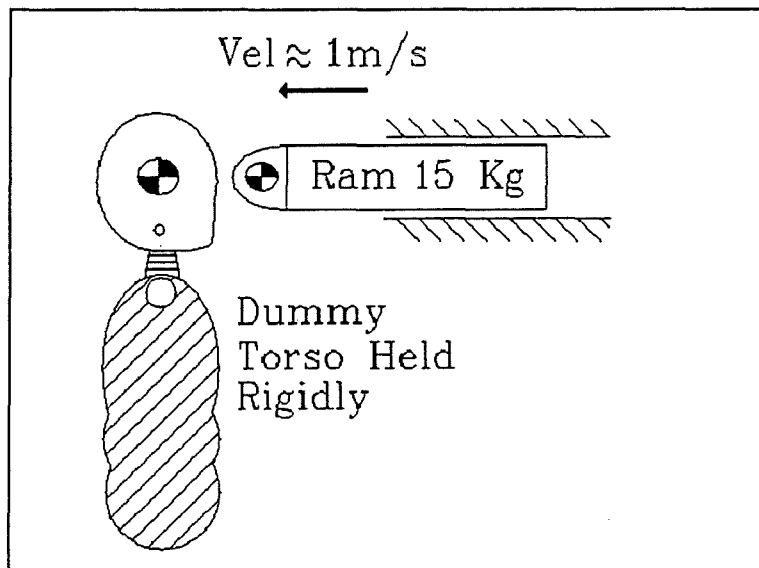
#### 11.1.1 NECK MODEL VALIDATION

In order to check the fidelity of the improved neck model and subsequently alter the model, it was necessary to obtain a

dynamic response of the dummy neck to a known load. The specification for such a test was;

- 1) Test must be dynamic in order that the effect of damping and friction can be assessed
- 2) Input must be known so that it can be modelled using MADYMO3D
- 3) Measurements of response must be able to be compared with MADYMO3D output
- 4) Response of neck must be able to be isolated from the input

The first concept for a validation test was to impact the head of the dummy with a ram. The torso of the dummy was held rigidly, therefore the response of the head to the ram impact would be defined by the neck and the interaction



**Figure 11.7** First validation test for new neck model. Head of dummy impacted by a 15 Kg Ram

between head and ram.

The ram was restricted to only a uniaxial movement and was fitted with a blunt wooden impact head. The ram was accelerated to the required speed by a rubber chord catapult system. The ram is in free flight just before impact. There was some concern over possible damage to the dummy, therefore the forward movement of the ram was limited by ties to approximately 200mm. Several tests were conducted using this test method at two velocities of impact. Unfortunately after the tests were complete, a problem with the test method and the data acquired became apparent.

It had been hoped that accurate data for the dynamic response of the dummy flesh could be obtained from either the dummy manufacturers or from a separate test. This data was required to create the MADYMO3D model of the ram test. The interaction between the ram and the dummy head is obviously an important factor that governs the head response. Thus accurate data for this parameter was required in order to be able to create the model. However, this data was not known by the dummy manufacturers<sup>1</sup> and therefore could not be supplied by them. The only possible way to find this data was therefore another dynamic test of the dummy flesh itself. Methods of testing to obtain this data were examined, but no simple solution was apparent. The deflection of the dummy flesh under a dynamic load would be under approximately 5mm, if no permanent damage to the dummy was to be inflicted. The problem was in measuring this deflection accurately in the time domain. The high speed cameras that were available could not be focused close enough to the subject. Without a close view of the dummy flesh it was not possible to get a high enough film or video resolution to yield accurate displacement measurements. It would have been feasible to measure the displacement with a linear displacement transducer. But this would have required the construction of a complicated test rig and the purchase of an accurate transducer. Therefore it was decided to abandon this test method and conduct a different test.

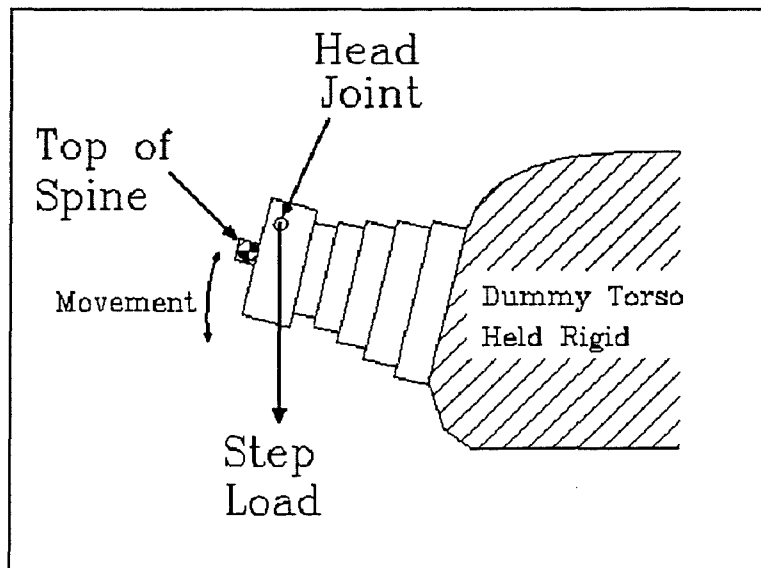
There was some deliberation over the form which the new validation test should take. The neck response had to be accurately measured when subjected to a totally known load. This load could not be a function of any other factor, like the flesh

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<sup>1</sup> IW-TNO of the Netherlands, who also developed the MADYMO software

in the previous test. The next test concept was to attach the dummy torso in an upright position to the RSEL dynamic impact rig. The sled could then be decelerated from a given velocity and the response of the dummy measured. The problem with this test method would be the measurement the head and neck displacement. In order to gain accurate measurements of the head and neck displacements it would be necessary to use an on-board camera, ie; a camera mounted on the sled which would allow a close view of the dummy movement. This was not able to be easily achieved at RSEL.

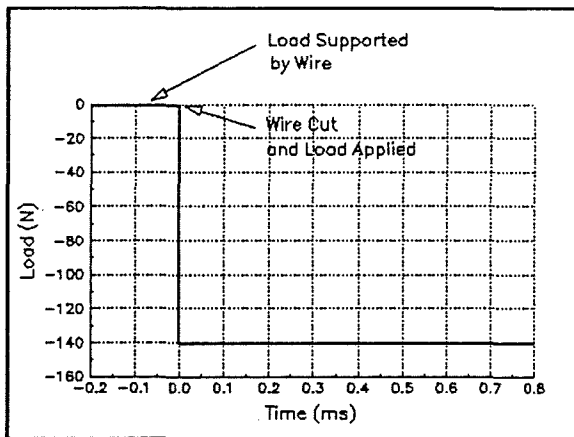
A simpler experiment was therefore required. Figure 11.8 shows a sketch of the test equipment that provided the actual validation data. The dummy was laid horizontally on its back and the torso rigidly located. A



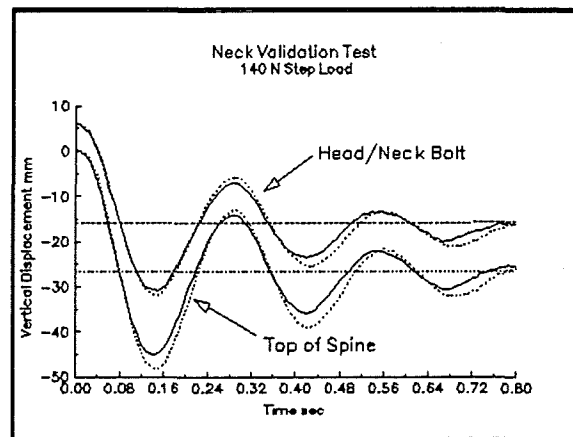
**Figure 11.8** Neck model validation test. 140.0 N instantaneous step load.

step load of 140 N was applied to the head joint bolt in the vertical direction. This load was applied by a known weight which was supported by a steel wire, which was cut when load was required. Thus the load was a near instantaneous step load as shown in Figure 11.9. The displacement response was recorded using a Kodak Ektapro 1000 High Speed Video Analysis system. Time history measurements of the upper neck displacement were then taken from the video recording. The response of the dummy neck is shown in Figure 11.10. Plots are shown for two tests (dotted line

and solid line) and for two points on the dummy upper neck structure. The response of the dummy neck obviously approximates to a damped single degree of freedom oscillation. From observation of the peak to peak time, the damped period of oscillation  $T_d$  is 0.28s. An equivalent stiffness can be calculated from the final resting place and the known force, but this bears little relation to the joint and contact stiffnesses that are defined in MADYMO3D.



**Figure 11.9** Input load of neck validation test



**Figure 11.10** Response of TNO P3 Dummy neck to 140 N step input

This data could now be used to develop the model further to yield a more accurate representation of the dummy neck.

#### **11.1.2 NECK MODEL DEVELOPMENT**

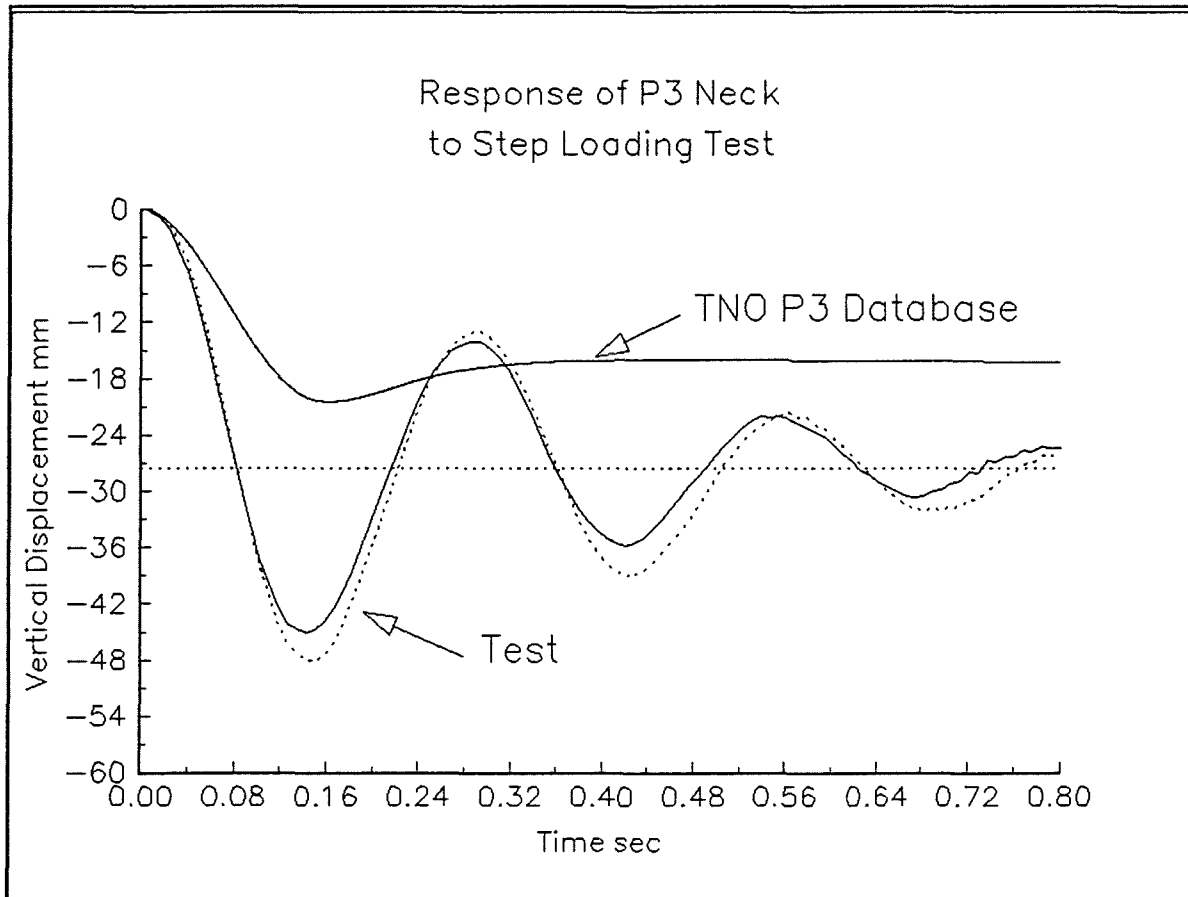
The next step in the creation of a validated neck model was to compare the results of a computer simulation of the validation step input test, with the actual test results. The MADYMO3D package does not have provision for an external force to be applied to an element. The step load was simulated by assigning the mass of the weights that were applied in the test to the head element in the model. The centre of gravity of the head was then altered to be co-incident with the neck-head joint, where the load was applied in the test. Gravity was then defined to be

normal to the CVS dummy back, and to run from  $t=0$  to  $t=\text{simulation end}$ .

The dummy torso had to be held rigid in the simulation. The first method to achieve this was simple, but did induce an initially inexplicable problem. Initially the torso was held rigid by attaching an extra anchor element of high mass and mass moment of inertia to the upper torso element of the CVS dummy. This element was linked to the torso with a very stiff flexion torsion joint. When the results of the simulation were examined, there were some very high (200g) acceleration spikes in the head and similar spikes in the neck load. This was initially thought due to instability in the neck contact model. The original P3 database neck model was replaced in the simulation. However, the spikes still remained. When the chest deceleration was examined (it had been assumed to be zero) the same spikes were evident. The spikes were finally attributed to the actual source, which was the very stiff joint between torso and extra anchoring element. This element and joint were subsequently removed. The torso was then held in place by increasing the mass and mass moment of inertia of the torso itself, to a near infinite level.

Once the dummy torso was rigidly held it was decided to compare the performance of the original TNO supplied P3 database neck with the step validation test. The standard database was altered only to simulate the step test, no alterations were made to the two joint neck representation (the input listing can be viewed in Appendix F). The simulation was run and the results compared to the test. Figure 11.11 shows the comparison of the test results and the results of the MADYMO3D simulation. It can be observed that the response of the MADYMO3D model is not a good

representation of the dummy neck response. The MADYMO3D model is too stiff (the final equilibrium position is too high) and over damped (no oscillation occurs). The examination of these results further supported the need for an improvement in the neck representation of the P3 dummy in MADYMO3D.

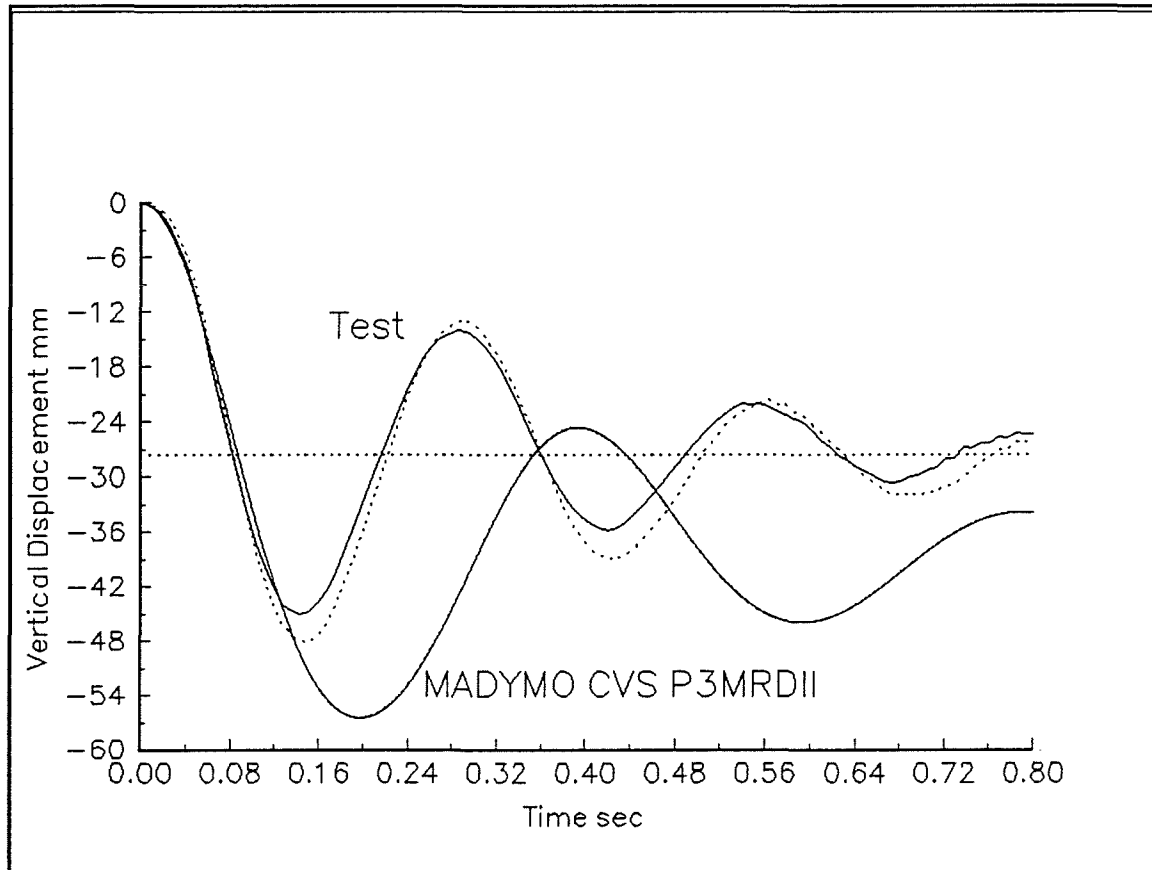


**Figure 11.11** Comparison of step input test results and MADYMO simulation using P3 database as supplied by TNO

The next step in the neck development was to compare the prototype neck model, as described in 11.1 with the test results. when this was done it was found that the response was not much better than that of the original shown in Figure 11.11. The model obviously required tuning of the stiffness and damping in order to improve the response. It was felt that the tuning of these factors was overly complicated by the use of ellipsoid contact interactions to define the neck stiffness. It was therefore decided to alter the neck model by removing the contact



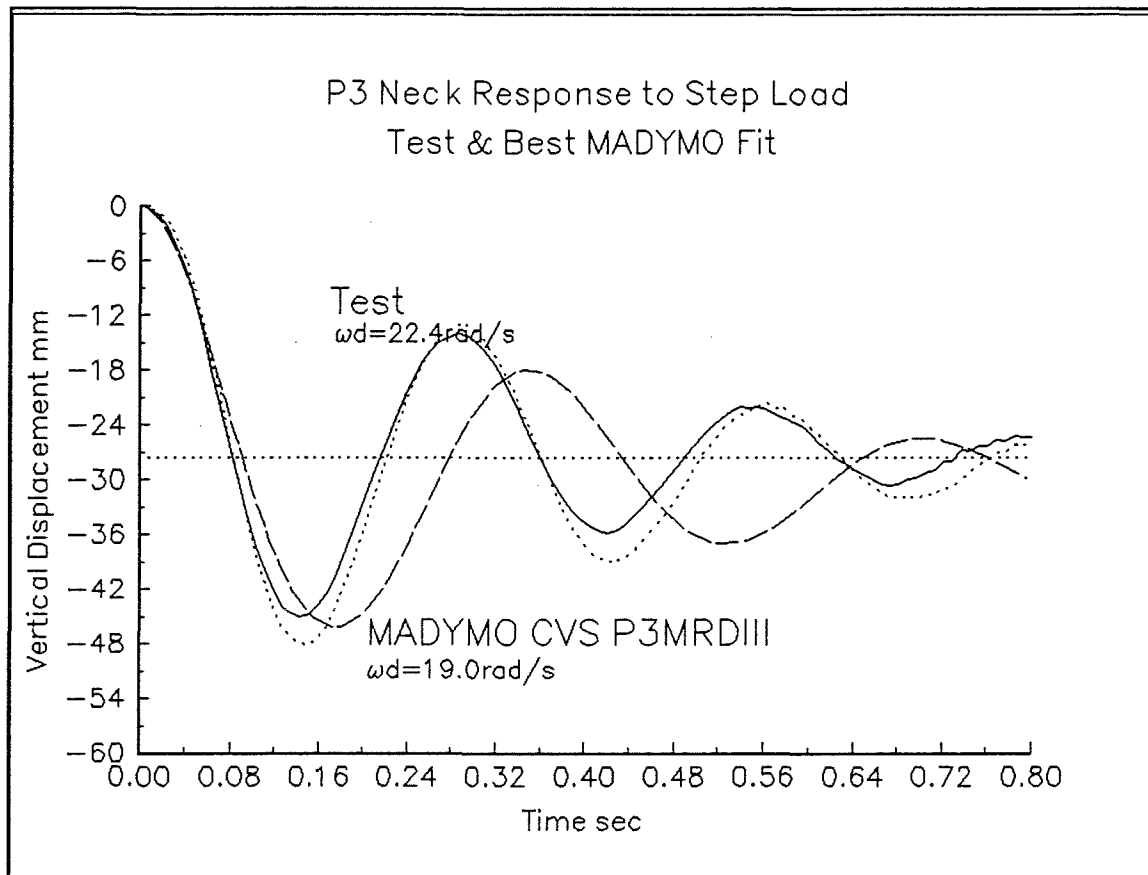
interactions and introducing stiffness characteristics to the joints between the neck elements. The joint stiffness that was initially used was that which was used in the original TNO P3 MADYMO3D database. The new database was designated P3MRDII. It was then used in a repeat of the step test simulation and the results are shown in Figure 11.12.



**Figure 11.12** Comparison of Step test and P3MRDII MADYMO database response

It can be seen that the response of the MADYMO3D model was better than the original. However, the neck model was obviously not stiff enough as the final equilibrium position is too low, and that the oscillation is not of the same frequency as the dummy response. The stiffness of the joints was then increased to yield the correct final equilibrium position. Once this was achieved the damping, mass moment of inertia and mass of each joint/element could be fine tuned to yield the best response of the model. The best response that was achieved is shown in

Figure 11.13.



**Figure 11.13** Comparison of best MADYMO simulation and P3 dummy neck response results.

The response of the neck model P3MRDIII is obviously not a perfect simulation of the test response. The final equilibrium position is fine and the damping ratio is approximately correct, but the period of oscillation is still too long. It was not possible to improve this model further. The frequency of oscillation is proportional to the stiffness ( $K$ ), and inversely proportional to the mass, mass moment of inertia and the damping constant. The stiffness and the mass could not be altered without affecting the final equilibrium point. The mass moment of inertia could not be reduced further without causing mathematical overflow in the MADYMO3D (Fortran based) programme. And the damping could not be reduced further without affecting the overall damping ratio. The simulation as shown in the figure above, was therefore considered the best possible with the

MADYMO3D version and model construction as used. It is included in Appendix F of this document.

The reasons for the differences between the response of the model and the actual neck are not clear. There are two possible explanations. Firstly, the joint flexion-torsion function that was used for this model was not measured

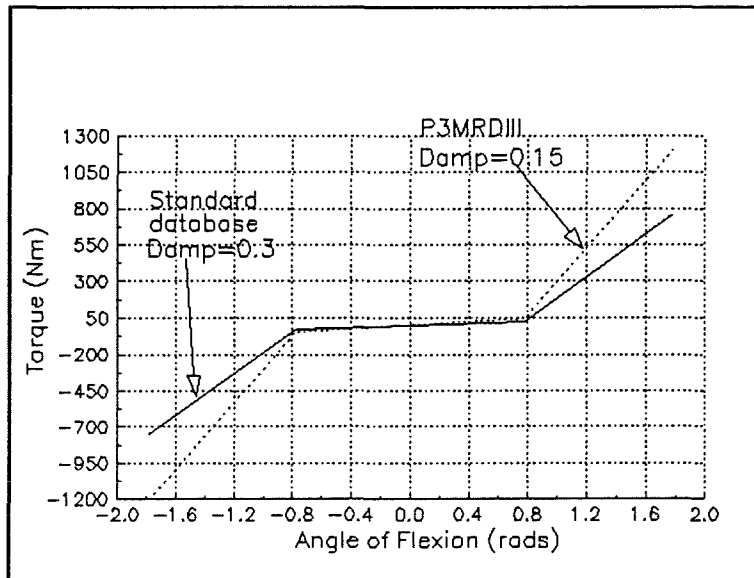


Figure 11.14 Joint stiffness function as used in the MADYMO neck model

but taken from the original database and then increased. This model does not include energy absorption (hysteresis) which may occur in the actual neck material. The shape of the flexion-torsion curve (as shown in Figure 11.14) may not be an accurate representation of the actual neck, but it would be difficult to gain an accurate measurement of this parameter.

The second possible reason for the differences in the model response is the method of representation of the neck construction. The actual neck of the P3 dummy is not constructed from a series of ball and socket joints (as used in this MADYMO3D version). The actual neck is constructed of a series of rigid (cervical) elements surrounded by a series of flexible outer rings. The neck is axially tensioned by the central steel cable. This construction will allow for some axial extension of the neck (the neck also has a small spring between the steel cable cap bolt and the top axis-atlas block) and some lateral movement

between the central elements. Neither of these factors can be modelled by the joints that are available in the current MADYMO3D model. The new MADYMO3D version, that will be released in the near future, does include several new joint models. These models may allow for an improvement in this neck model.

The neck model as it stands was not considered a poor representation of the dummy neck. The differences in the response, although significant, were not considered critical. It must be remembered that the neck model was designed to be used in a much shorter time domain than was measured in the step input validation test. The usual simulation time that is used in a car crash simulation is about 0.12 seconds. This means that the neck is usually not in the rebound phase. The critical factor that the neck model must portray is the initial deflection. The later stages of the oscillation are not important in these simulations. Thus the neck as it stood was a great improvement over the original database and was considered suitable to use in crash simulation.

#### 11.2 PROGRAMME OF SIMULATION USING THE IMPROVED NECK MODEL

There is some international debate over the importance of the chin-chest contact in neck and head injury. Janssen et al (1991) showed the effect of a lower chest stiffness on the neck loading of a TNO P3/4 dummy simulation. No known work has been conducted on the TNO P3 dummy whilst restrained by a framed child seat. This was obviously an area which required investigation. Another area of investigation that was considered important was the effect of the location of the fulcrum for neck bending. The fulcrum for bending in the child neck is in the C3 area of the neck, whereas the fulcrum in the adult is lower at the C5-C6

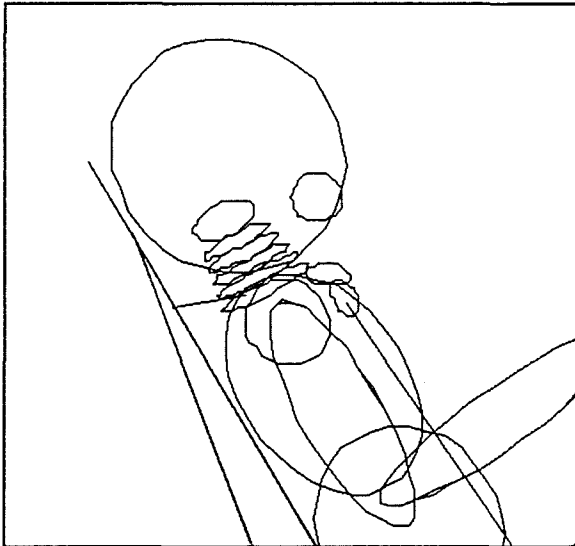
area. We would expect the child head to have higher head rotational accelerations, due to the shorter radius of rotation and therefore to have a higher injury potential. Also examined with the improved neck model was the effect of head mass on the neck loading. Children do vary significantly in development at particular age and we would expect children with a higher head mass to undergo a higher neck load in the crash environment. The final area which was investigated with the new neck model was the effect of the child seat shell inclination on the neck loading.

#### 11.2.1 THE EFFECT OF THE CHIN-CHEST CONTACT STIFFNESS ON THE INJURY POTENTIAL TO THE CHILD HEAD AND NECK

Up to this point no chin to chest contact had been included in the MADYMO3D simulations. Head and neck loading had not been considered an appropriate injury potential indicator, given that the MADYMO3D representation of the P3 neck was not thought to have good fidelity with the P3 dummy. This part of the investigation was designed to investigate the parameters which might contribute to non-impact head and neck injury. Therefore it was now necessary to consider the loadings in these areas and the chin to chest contact was likely to play a major role. The following section discusses the actual method for defining the chin-chest contact. After that there the results from the simulations which varied this contact.

##### 11.2.1.1 DEFINING THE CHIN-CHEST CONTACT

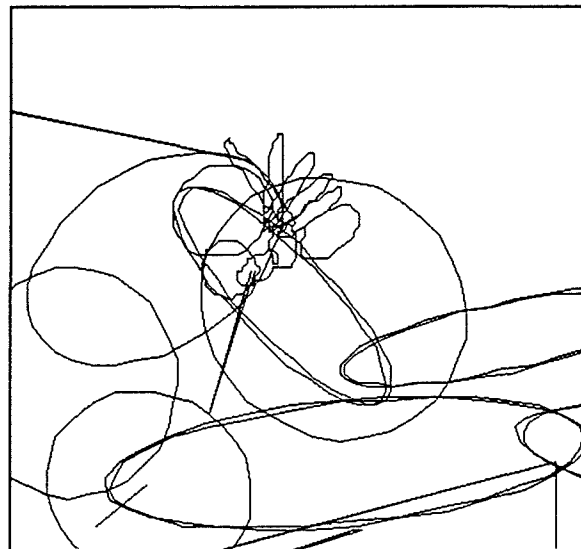
The chest shape as defined in the original P3 database was not an accurate representation of the P3 dummy. The rather complex upper torso shape was represented by a single ellipsoid of degree 2. It was therefore necessary to introduce a extra contact surfaces, in



**Figure 11.15** First method for introducing chin-chest contacts with two additional upper torso contact surfaces (ellipsoids)

the form of ellipsoids, at the front of the upper torso to allow for accurate location of the chin-chest contacts. The same was also true of the head shape and one extra ellipsoid was added at the location of the dummy chin. Figure 11.15 shows the configuration of the extra contact surfaces that were introduced. The upper torso has

two extra ellipsoids, this was a second attempt at modelling the chest contact. The first model comprised only the upper of these two ellipsoids. However even the two ellipsoids shown were not sufficient to model the chin-chest contact satisfactorily. The problem with this contact model is shown in Figure 11.16. The chin ellipsoid



**Figure 11.16** Head location in standard FCS CVS with two ellipsoid upper torso contact model at  $t=120\text{ms}$

is pushed down the upper torso by the extra ellipsoid contacts and then the head is free to penetrate the upper torso completely. The chin contact then passes behind the two extra torso ellipsoids and the neck is severely bent. This movement occurs because of the method of defining contact interactions in MADYMO3D. It is not possible to limit the vector direction of the contact force.

The force-penetration function that was used for the chin-chest contact is shown in Figure 11.17. This function was taken from a sample MADYMO application that is supplied with the MADYMO software. The application is

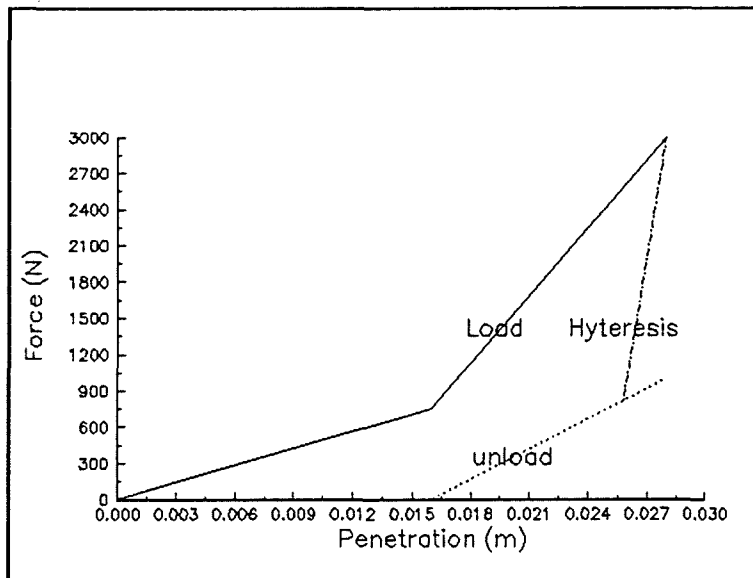
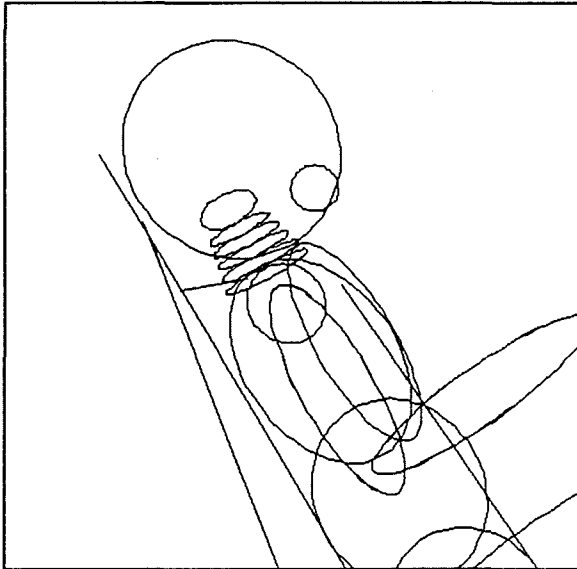


Figure 11.17 Force-Penetration characteristic for the chin-chest contact.

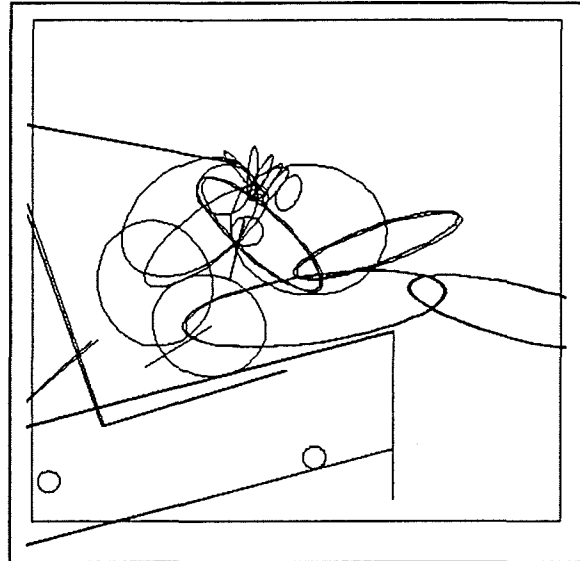
actually using the

MADYMO 2D database for the TNO P3/4 dummy, but it was not thought that the function would be very different for the P3 dummy. This was the only data that was available for input into the programme. It may have been possible to measure this characteristic, but it is a little subjective as to which angle the contact actually occurs. Therefore it was felt that the data taken from the P3/4 application would be the most accurate.

The utilisation of a plane as the extra chest contact surface may have been a possible method of limiting the direction of the chin-chest contact force. The force is always normal to the plane. However, a single plane would not define the contact surface of the chest adequately. Therefore it was decided to continue with a single ellipsoid, which was then progressively increased in size to improve the contact interaction. The final design was an ellipsoid which ran the full length of the upper torso, as shown in Figure 11.18. This contact surface model did not have the same penetration problem which the earlier models exhibited (see Figure 11.19).



**Figure 11.18** Final chin-chest contact surface configuration

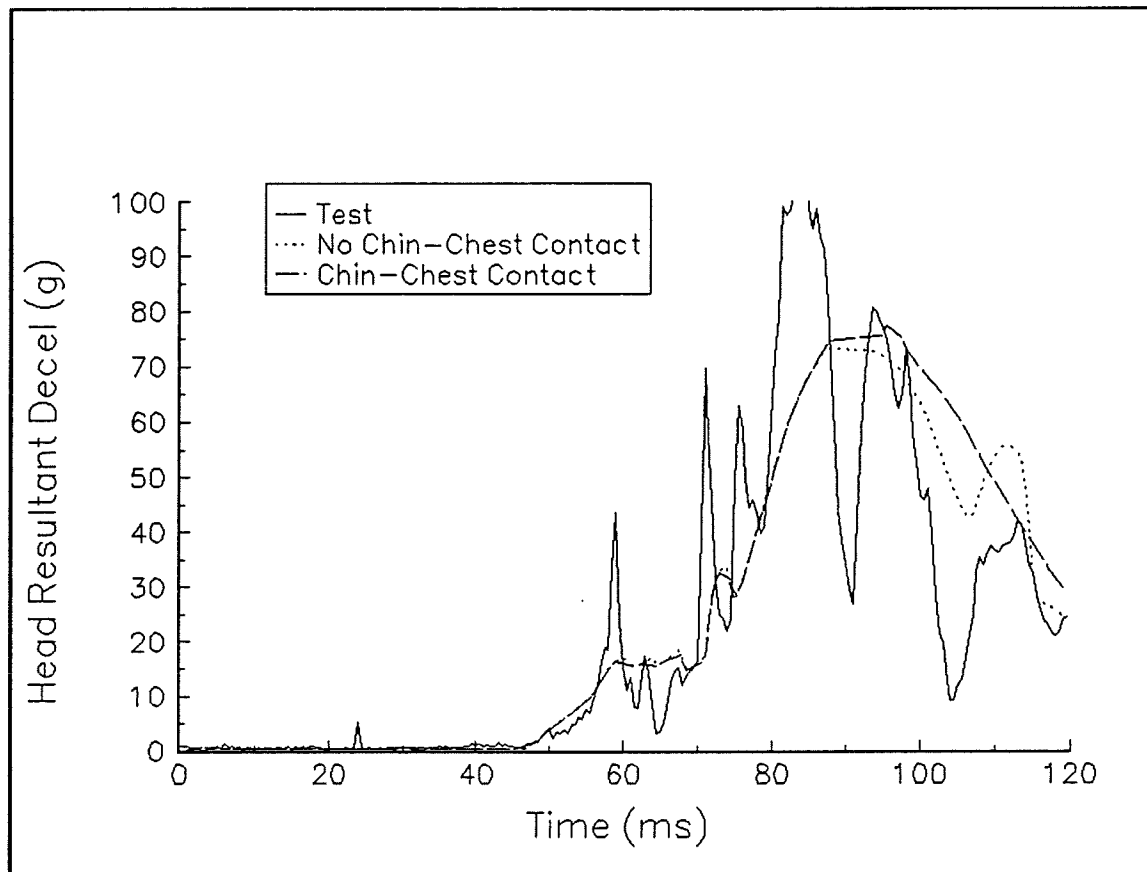


**Figure 11.19** Finalised chin-chest model at time  $t=120\text{ms}$

The next step that was conducted was a comparison of a simulation with the chin-chest contact, a simulation without and the actual test result that was used to validate the first model (Test 1922). This was a simulation of the test of a surrogate FCS restrained with an adult lap belt. It was expected that some of the differences between the head acceleration in the test and CVS would be resolved by the new neck model and the introduction of the chin-chest contact. This was not the case. Figure 11.20 shows the head resultant decelerations compared, the new neck model or chin-chest contacts had made little difference to the overall curve shape. Either the chin-chest contact stiffness was wrong or there were other factors which were influencing the head deceleration.

It was decided to continue with the investigation of the effect of the chin-chest contact stiffness on the injury potential to the child head and neck, with the model as it stood. The fact that the model head deceleration was not a perfect representation of the dummy deceleration was not considered critical.





**Figure 11.20** Comparison of CVS with new neck model and chin-chest contacts (or not) and test 1922

Conclusions about injury potential were based upon relative changes in deceleration between simulations, rather than based upon certain absolute values. It has already been discussed that little information is available on child injury biomechanics or tolerance levels. There is no information which can show which dummy or computer model is a better human surrogate. This improved neck model (P3MRDIII) has been shown to have a more dummy-like movement. Therefore the planned work with the model was continued.

#### **11.2.1.2 RESULTS OF THE INVESTIGATION INTO CHIN-CHEST CONTACT**

The investigation into the effect of a variation in the chin-chest contact stiffness, comprised the study of the head accelerations and neck forces in simulations of the surrogate FCS in a standard configuration. The results of three simulations

will be discussed in this section. Other simulations which were conducted with varying chest stiffness will be discussed in the following sections of this chapter.

The three simulations that were conducted were all lap belt restrained surrogate FCS based upon the simulation SIMLG2. The dummy database was of course P3MRDIII. The three chin-chest stiffnesses were as follows;

- 1) No chin-chest contact
- 2) Standard chin-chest contact as used in MADYMO sample application
- 3) 0.5 x the standard chin-chest contact

Two factors were used to assess the injury potential to the head and neck; firstly the load in the C1-C2 neck joint and secondly the angular acceleration of the head. These factors were considered to provide the most accurate assessment of the injury potential that was available. Injury potential was simply assessed by a comparison between the height and shape of the curves. No accurate or reliable tolerance levels were available to make more complex injury evaluations.

Figure 11.21 shows the comparison of the force-time history plots for the three chin-chest contact configurations. It can be seen that there is almost 1 kN difference in the neck loads of the CVS with the full stiffness chin-chest contact and that without such a contact.

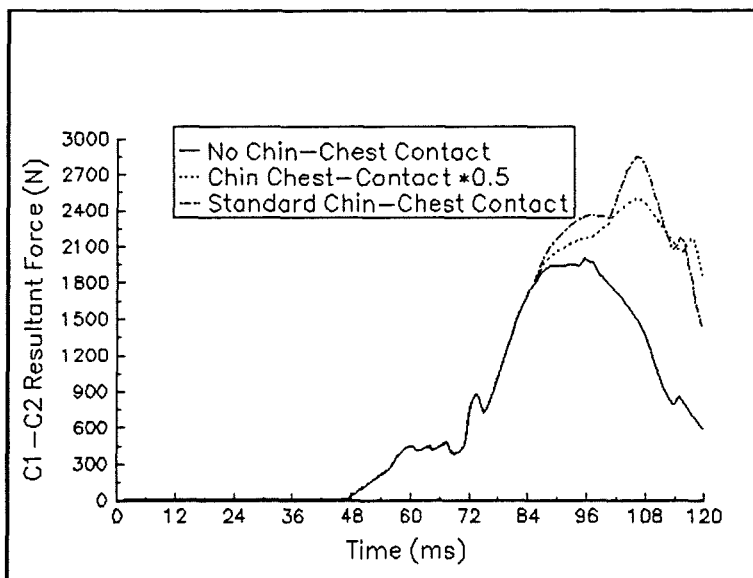
The reduction of the chest stiffness to half the original value, limits this difference to around 600 N. A similar change in injury potential can be observed in the head angular acceleration results (Figure 11.22). The effect of the chin-chest contact can be clearly seen in the later stages of the time-history plot. The first peak in these plots (positive), which is common to all the

simulations, is angular acceleration due to the inertial loading of the head and the restraint by the neck. The second peak is clearly due to the effect of the chin-chest contact.

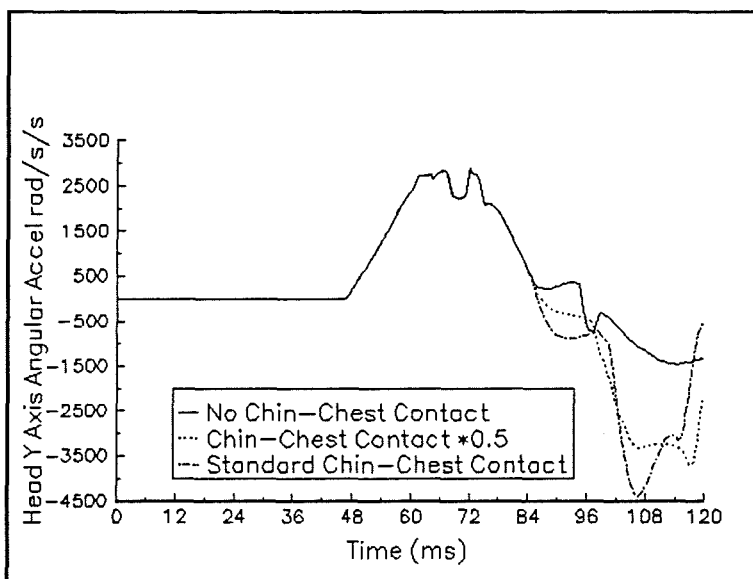
The head is accelerated negatively (rotation down at back of head) by the force of the contact. The contact peak can be observed to be much higher than the first.

The results suggest that the chin-chest stiffness plays a major role in the

dynamic response of the crash victim's head. There is no real biomechanical information that can be used to assess the biofidelity of any of these contact models, therefore these results can only provide evidence of the importance of this contact. For the next phase of child dummy development it is strongly advised that more information should be gathered in this area. There is obviously no point in producing a perfect surrogate of the human neck, if the chest stiffness is ignored.



**Figure 11.21** Comparison of C1-C2 joint resultant forces of CVS with various chest stiffnesses



**Figure 11.22** Comparison of angular acceleration results of CVS with various chest stiffnesses

### 11.2.2 INVESTIGATION INTO THE EFFECT OF HEAD MASS ON THE OCCUPANT NECK LOADS

There is a variation in the relative proportions of the body parts of all people, this is particularly true of children. It was expected that the relative head mass of the child would be an important factor in the potential injury to the child neck. The head of the child has already been shown to be large in proportion to the neck and any variations, in particular increases, would be likely to increase the injury level to the neck. This is of course due to increased inertial loading from a higher head mass. Thus in the standard simulation SIMLG2 with the P3 database P3MRDIII the head mass was varied and the resulting load on the neck assessed.

The CVS was run with three head masses; the standard mass, a 5th percentile head mass and a 95th percentile mass. No data was readily available which accurately gauged the 3 year old child's head mass for the different percentiles. Therefore the head mass was assumed to vary in proportion with the body mass. The body masses for the 5th and 95th percentiles was taken from Snyder et al (1977) and the head mass of the standard P3 database was varied in proportion. Thus the head masses used were;

5th %ile	2.048 Kg
50th %ile	2.625 Kg (standard TNO P3 database)
95th %ile	3.203 Kg

Simulations were conducted with the chin-chest contact and without. This was done because of the uncertainty over the actual chest stiffness. This proved to be an appropriate strategy. The injury potential to the neck was assessed in terms of the load at the C1-C2 joint. This particular joint was chosen as non-impact neck injuries appear to occur almost exclusively in this region

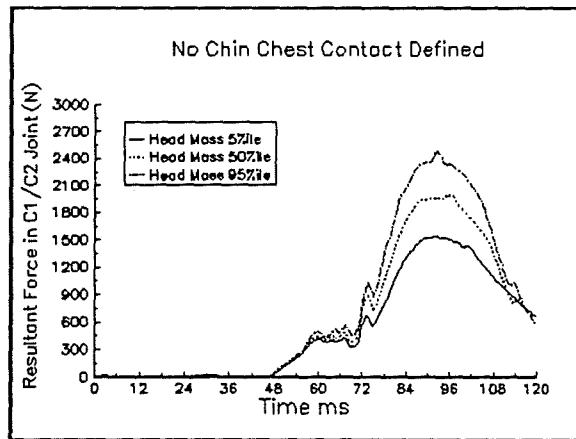
(see Huelke et al (1992)). The comparisons of the resulting neck forces are shown in Figure 11.23 to Figure 11.28. The left hand graphs are simulations without chin-chest contact and the right hand graphs are with this contact.

The no contact results exhibit the expected result, in that the calculated neck load increases with the mass of the head. The difference in the peak loads between the 5th %ile and 95%ile case is almost 1 KN. However, the peak loads in the chin-chest contact simulations actually slightly decrease with head mass. The peak loads are also generally higher than in the CVS without chin-chest contact.

The simulations that involve chin-chest contact can be seen to exhibit the same characteristics as the no contact simulations until contact occurs. ie; until contact the smaller head mass induces a lower neck load due to the lower inertial load. When contact occurs (at around  $t = 96$  ms) the smaller mass head is accelerated greater and than the larger masses, because of smaller mass. This then transfers more load to the neck. A comparison of the accelerations can be seen in Figure 11.29.

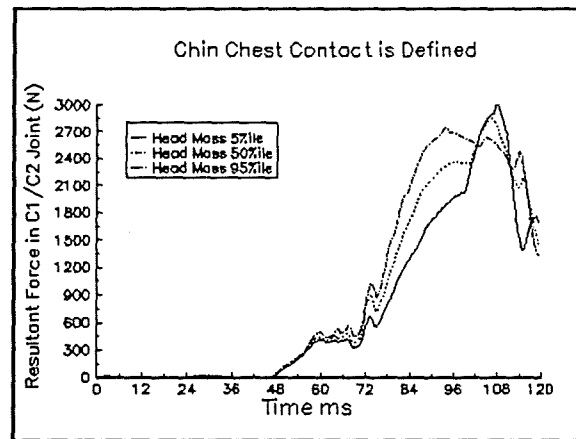
The effect of the head mass on the injury potential to the child neck, has been shown to be partially dependent upon the chest stiffness. Thus again, the lack of accurate biomechanical data on the human child prevents the further progress in this area of the investigation. If it is assumed that the chin-chest contact that is used for these simulations is stiffer than in a real child (which seems likely), the effect that is illustrated here will not be so pronounced. Therefore a relatively high head mass could be seen to be a high neck injury risk.

## NO CHIN-CHEST CONTACT

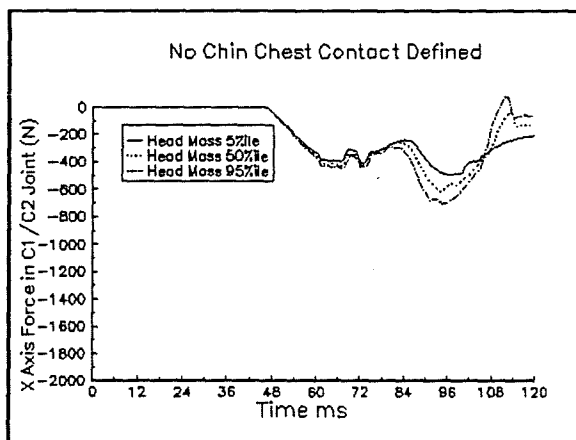


**Figure 11.23**

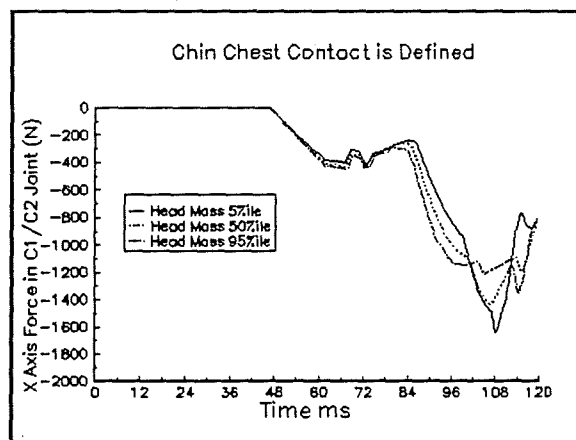
## CHIN-CHEST CONTACT



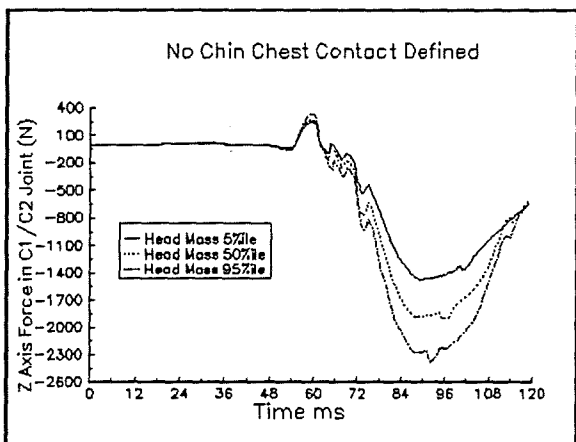
**Figure 11.24**



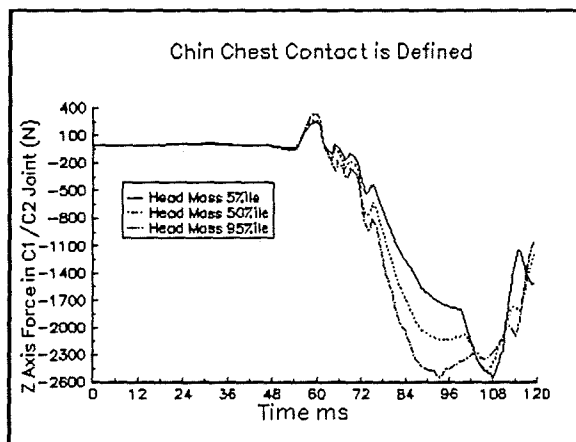
**Figure 11.25**



**Figure 11.26**

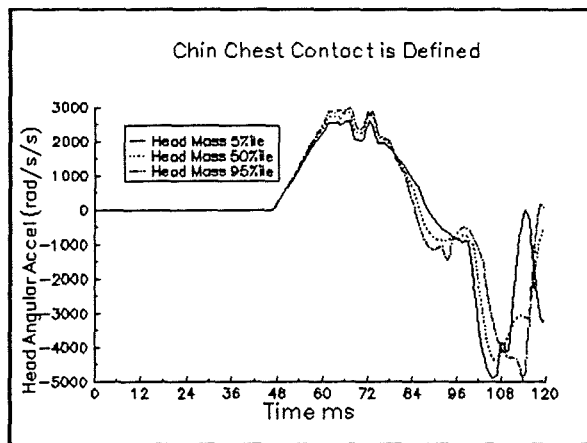


**Figure 11.27**



**Figure 11.28**

It should be noted that all of the loads calculated by MADYMO3D in these simulations are above the tolerance levels stated by Stürtz (1980) and Mertz (1991), in fact many of the loads are double or treble these criteria. However, as stated in 3.3.2 these criteria were not based upon the TNO P3 dummy in a non head impact crash environment and thus are not directly applicable. It



**Figure 11.29** Comparison of angular accelerations for CVS with various head masses and chin-chest contact

seems unlikely that the loads observed in the standard simulations are consistent with a neck injury. If they were, we would expect a larger proportion of neck injuries in real accidents. The standard test simulation exhibits a tensile load (z axis) of approximately 1900 N. Based on the evidence

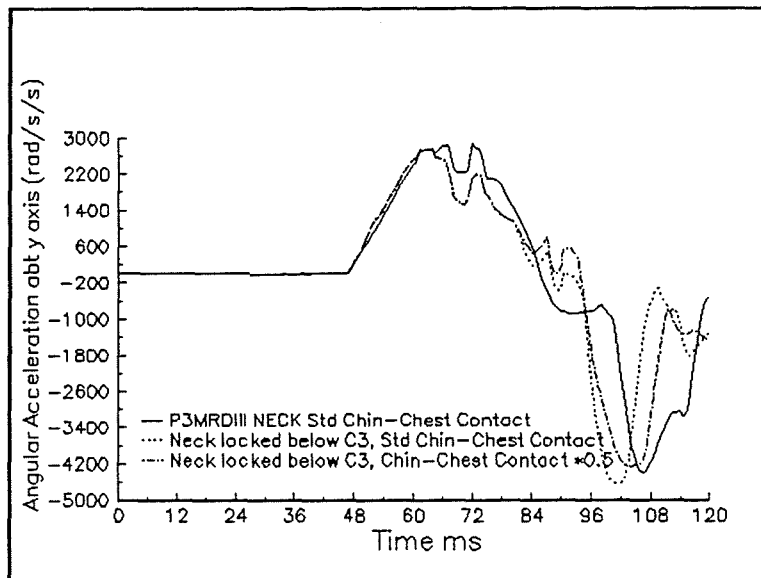
that is available from accident case studies, this value would seem to represent a survivable load in most children.

### 11.2.3 INVESTIGATION INTO THE EFFECT OF THE LOCATION OF THE FULCRUM FOR BENDING IN THE CHILD NECK

In normal situations the fulcrum for bending in the human child neck is at the C3 level rather than the C5-C6 level that is usual in adults (see Huelke et al (1992)) (cervical vertebrae are numbered from C1 at top to C7 at base). It is not clear whether this is true in the crash loading situation, but bending is likely to be initiated and greater in the C3 region. The expected effect of the C3 joint as a fulcrum for bending is an alteration in the kinematic movement of the head and an increase in the angular acceleration of the head. An increase in angular acceleration would be expected because of the reduction in the radius of rotation. In terms of injury the important factor here is the angular acceleration, but also of concern is the neck load. This may be affected because of the increase in inertial load and the alteration in kinematics leading to alterations in the chin-chest contact.

The model was altered for use in this part of the investigation by introducing a very high joint stiffness to all joints below C3. Those joints above C3 remained unaltered. Simulations were run with the standard chin-chest contact stiffness and a contact of half this value. The results were assessed in terms of head angular acceleration and C1-C2 neck load. Comparisons were made with the standard P3MRDIII neck model response.

The results in terms of angular acceleration are shown in Figure 11.30. It can be seen that the accelerations are very similar in terms of both shape and peak value for the improved neck model and the raised fulcrum simulations. In

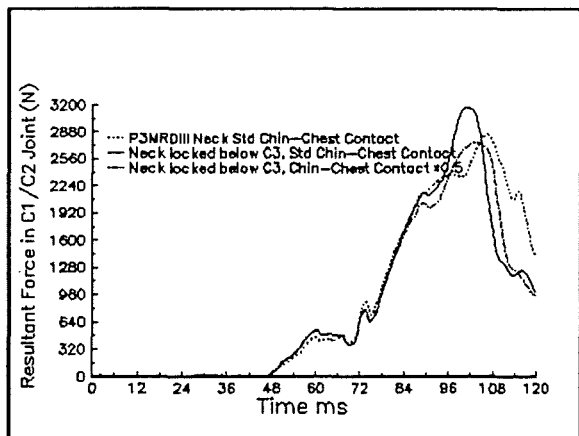


**Figure 11.30** Comparison of angular accelerations for investigation of effect of fulcrum position

addition the chin-chest stiffness has made little difference to the head response. It is thought that the expected increase in head acceleration, because of the reduction in radius, was counter balanced by the effective increase in neck stiffness. In addition the chin-chest contact places a restriction on changes in kinematics.

Both the resultant (Figure 11.31) and z axis (Figure 11.33) neck force results show little difference between the various neck and chin-chest contact configurations. Only the x axis results show a significant change in performance. Figure 11.32 illustrates the



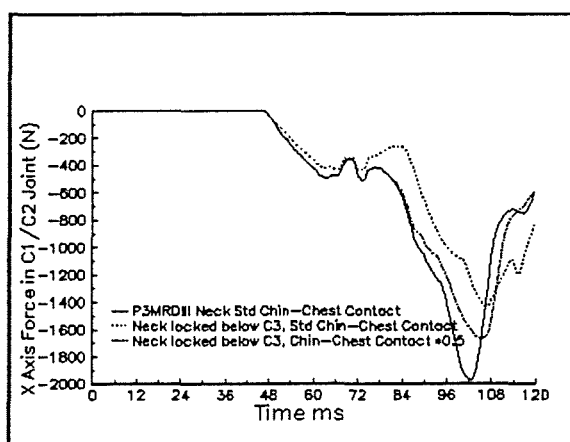


**Figure 11.31** Comparison of resultant force in C1-C2 joint for neck fulcrum position investigation

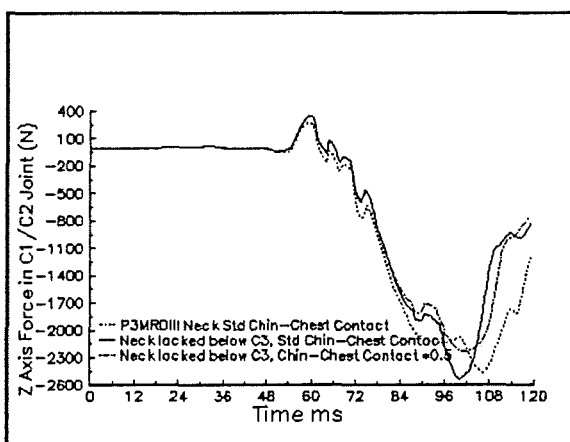
difference in the x axis neck force response. The simulation with the neck that is locked below the C3 joint exhibits an x axis load that is around 600 N or 40% higher than in the simulation with the standard

P3MRDIII neck model. This is due to the change in kinematics of

the head movement and the resulting change in direction of the force from the chin-chest contact. In the C3 locked case the head contacts the chest when in a more horizontal position and therefore receives the contact force in a direction closer to the head x axis. This result is rather interesting in terms of injury biomechanics. This type of shear force could contributory cause of the C1-C2 dislocations and fracture injuries that are seen in real accidents. Therefore the extent and type of neck injury may well depend upon the stage of development of the child's neck, ie; the location of the fulcrum for bending.



**Figure 11.32** Comparison of C1-C2 joint x axis force for neck fulcrum position investigation



**Figure 11.33** Comparison of z axis c1-c2 neck loads for neck fulcrum position investigation

#### 11.2.4 INVESTIGATION INTO THE EFFECT OF A RECLINED SEATING POSITION ON THE INJURY POTENTIAL TO THE CHILD

The tests that were conducted with a reclined seating position, see chapter 6, exhibited high peak rebound values in the head accelerations. This suggested that the head was being rebounded with a greater force. Which lead to the possible conclusion that the neck was put under higher load conditions than with a child restraint in the upright configuration. There obviously was some concern that the reclining of framed child seats could increase the injury potential to the child neck. Many of the production framed child seats that are currently being sold, do have the capability of reclining.

It was not possible to test this hypothesis with a dynamic test. There was no capability for measuring the neck loads of a TNO P3 dummy as there was no commercially available neck load transducer. It was therefore necessary to use the MADYMO3D CVS for

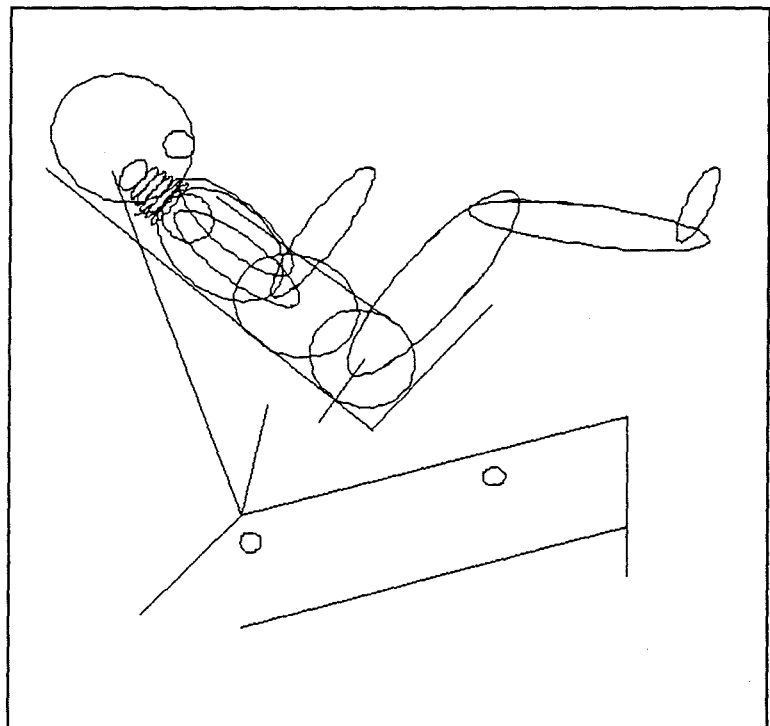
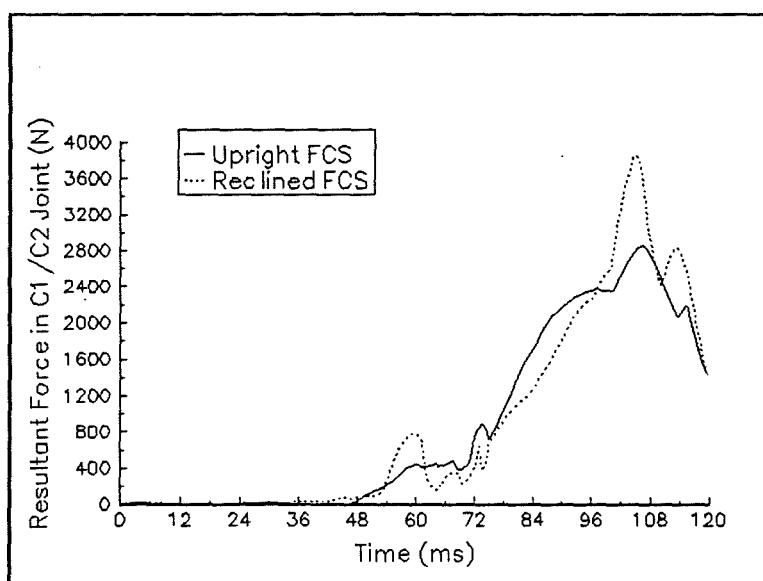


Figure 11.34 Image of CVS of Reclined Framed Child Seat at  $t=0$

investigation of this possible injury mechanism and as had already been stated, this was one of the reasons for creating the improve neck model database P3MRDIII. In order to simulate the reclined seating position it was necessary to alter the location of both the dummy database and the FCS seat planes. The location

and inclination of the new points was taken from a drawing of the surrogate FCS. In addition the centre of gravity of the simulated FCS was altered to that of the reclined surrogate FCS. The resulting simulation configuration is shown in Figure 11.34. The newly configured FCS was then subjected to identical acceleration inputs to previous upright simulations. No other alterations were made to the input data, the FCS was anchored with a surrogate lap belt. The results of the simulation support the theory of higher neck loads in reclined framed child seats.

Figure 11.35 clearly shows that the peak resultant force in the

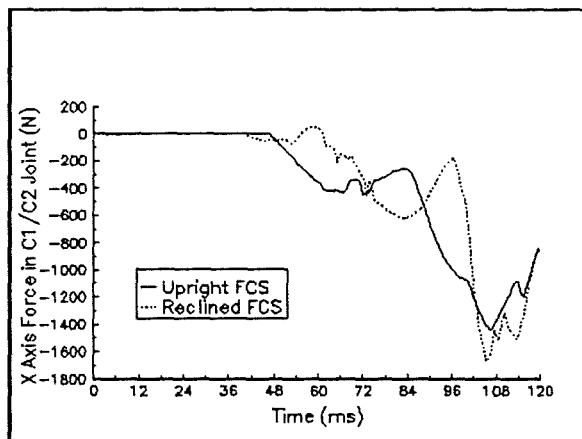


**Figure 11.35** Comparison of Resultant Neck forces calculated in upright and reclined FCS simulations

C1-C2 joint of the reclined simulation is approximately 1 KN higher than in the upright case. When the x axis (Figure 11.36) and z axis (Figure 11.37) components of this force are examined this extra load can be seen to be mainly an

extra neck tension (z axis).

In addition the peak head angular acceleration is much higher in the reclined case than in upright case ( $11070 \text{ rad/s}^2$  compared with  $4412 \text{ rad/s}^2$ . see Figure 11.38). The higher peak neck loads and head angular accelerations are due to a longer period of free flight of the head, whilst the head becomes more horizontal. It is not until the head becomes horizontal that the neck can

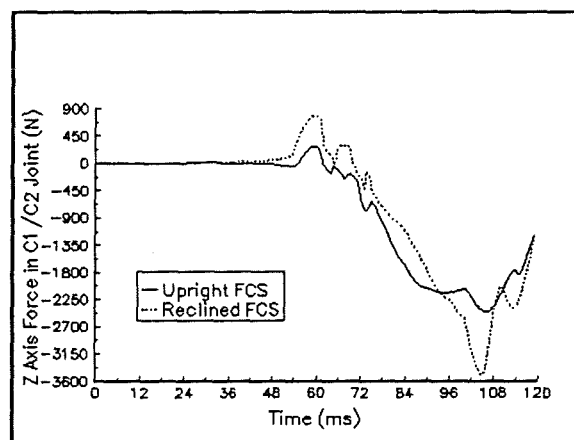


**Figure 11.36** Comparison of Neck x axis force as calculated in upright and reclined FCS simulations

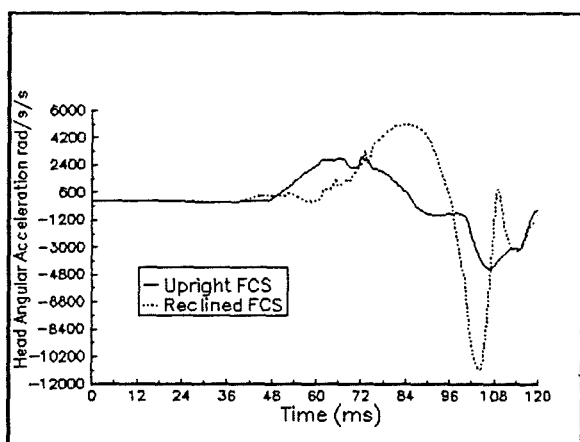
contribute to the higher head and chest decelerations as observed.

This part of the overall project investigation concluded the simulation work.

restrain the movement. This extended free flight leads to higher head velocities leading to higher chin-chest contact loads. Also the increased free flight time reduces the actual stopping distance of the body as deceleration occurs later in the crash envelope. This will



**Figure 11.37** Comparison of Neck z axis force in upright and reclined FCS simulations



**Figure 11.38** Comparison of angular accelerations calculated in upright and reclined FCS simulations

12 MISUSE AS OBSERVED IN A  
SAMPLE OF CHILD RESTRAINTS

## 12 MISUSE AS OBSERVED IN A SAMPLE OF CHILD RESTRAINTS

The incorrect use of a child restraint can cause degradation of performance and thus increase the injury potential to a child. In addition misuse affects the apparent effectiveness of child restraints as seen in statistical accident data, as more children are injured whilst using restraints. The mode of misuse is the critical factor which determines the amount of performance degradation. It is often difficult for the child restraint designer to comprehend the possible manner in which the restraint can be misused. It is therefore necessary to gain both an understanding of the extent of the misuse problem and information on the modes of misuse in the real life situation. The study presented here does not provide an accurate estimate of the level of misuse in the UK. The sample is likely to be biased towards misuse. However, this sample does provide evidence of the modes of misuse and a comparison of misuse levels in the different restraint types.

### 12.1 METHODOLOGY OF DATA COLLECTION

The data collection was conducted as part of a series of fitting checks on child restraints that were viewed in cars. The child restraints were viewed as fitted and used by the parents. The child user was available for the assessment of harness or belt adjustment and appropriate size. All of the restraints were examined by a member of the RSEL staff who were all familiar with the correct mode of use for each child restraint. Notes on the misuse of the restraint were made on a purpose designed form, which prompted the examiner to check for various misuse modes. The child restraints were categorised into one of the following four types;

Infant Carrier	A specific infant carrier or a combination 2 way device, used as an infant carrier in a rearward facing configuration. Designed for the children up to 10 Kg mass.
Framed Child Restraint	A specific toddler seat or combination 2 way device used in a forward facing configuration, with an integral harness to restrain the child and anchored with an adult seat belt. Designed for children of 9-18 Kg mass.
Four point/ Two point	A toddler seat with an integral harness to restrain the child and anchored with either four or two point strap system. Designed for children of 9-18 Kg mass.
Booster Seat/Cushion	A purpose built seat or cushion which is designed to aid the correct location of an adult seat belt when used by a child.

The misuse modes were defined as follows;

#### **Harness's**

Slack in Harness	Any unreasonable amount of looseness in the harness.
Harness Misroute	Harness is routed incorrectly through the child restraint shell or structure. eg; through wrong slots in shell.
Harness Maladjusted	Harness incorrectly located on child. eg; lap belt over abdominal area rather than hips.
No Crotch Strap	Crotch strap missing or not used on a child restraint which is designed to use one.

#### **Child Restraint Anchorage**

Slack in Adult Belt	An adult belt which was not adjusted to the child restraint manufacturers specification.
Slack in Anchorages	Anchorage straps which were not adjusted to the child restraint manufacturers specification.
Adult Belt Misroute	Adult belt is incorrectly routed on child restraint. eg; buckle lies on restraint frame.

Anchor Strap Misroute	Anchor straps on four or two point seats are incorrectly located at the vehicle anchorage or on child restraint.
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#### Other Faults

Inappropriate Device	Device is inappropriate for size of child. Child too large or small.
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Other	Other miscellaneous errors.
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The bulk of the child seats were observed at a publicised checking day at a Bedfordshire Supermarket, on Sunday 17th March 1991. The checking day was organised by the Road Safety Officers of Bedfordshire County Council in response to public concern over the fitment of restraints in daily use. The sample also includes child restraints that were checked at the Road Safety Engineering Laboratory (RSEL) on various occasions. The child restraints observed at RSEL were official checks on behalf of the Barnet Trading Standards Office.

It must be noted that the sample of child restraints presented in this document is likely to be biased towards misuse. The sample was self selecting, in that the child restraint owners choose to attend the checking day. Only parents who were concerned about their child seats and child safety were in attendance. The sample could be considered to exclude child seats owned by parents who were certain that the child seat is used correctly. However, many parents appeared to be surprised that their seat was misused and that it mattered, they merely attended the checking day as a double check on the safety of the device. Due to the possible bias in the sample no conclusions can be drawn about the overall misuse situation.



## 12.2 RESULTS OF THE DATA ANALYSIS

The results of the checks are presented in tabular (see Appendix G) and graphical form. Figure 12.1 shows the levels of misuse for each of the four child restraint types. Of the child restraints seen only the booster

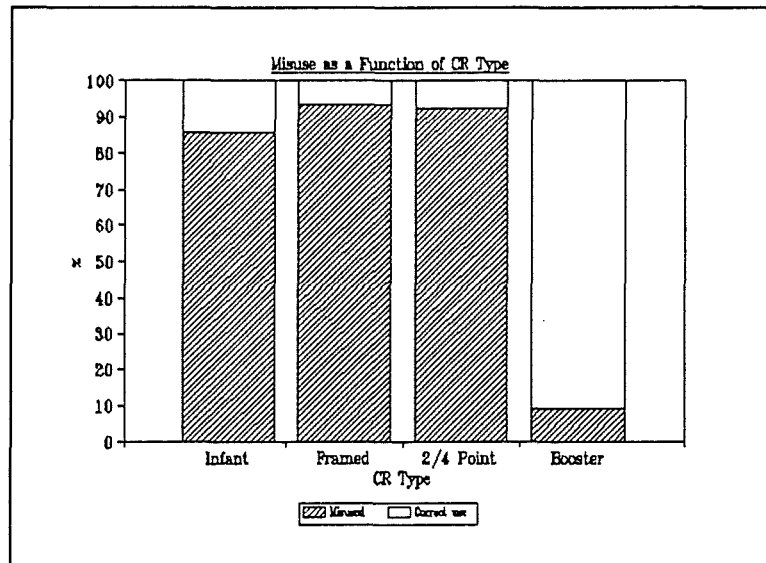


Figure 12.1 Misuse levels observed in the four child restraint types

cushions and seats had a good level of correct use (you can do little wrong with this type of restraint). The other restraints (infant carriers, frame type and four point) all had misuse levels of around 90%, but as has already been stated, the sample was biased and therefore it is not likely that this represents the actual misuse level.

Of the 61 child restraints that were examined, half (30) were frame type restraints. Whether this represents the size of the restraint population or a higher concern over misuse of these seats, it is not known. The misuse modes are presented broken down into the four child restraint type categories in Figure 12.2 to Figure 12.5.

One of the most common types of misuse recorded was slack. This was apparent in both the harness and the anchorage straps of the child restraints. Of the child restraints that were misused, the number of restraints with harness slack was 67% of infant carriers, 54% of framed seats and 42% of 4point/2point seats.

Harness maladjustment, in the form of incorrect lap belt location, was also a common misuse type.

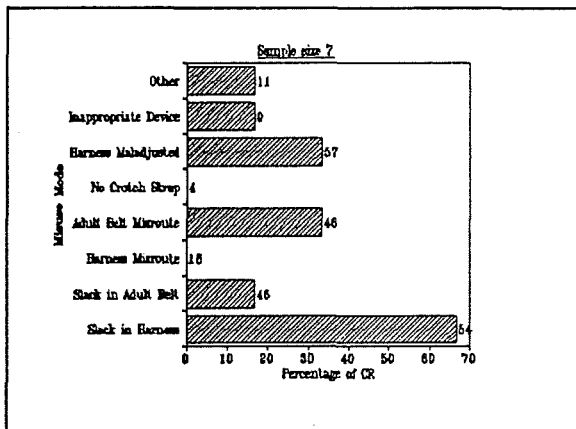


Figure 12.2 Misuse modes in infant carriers#.

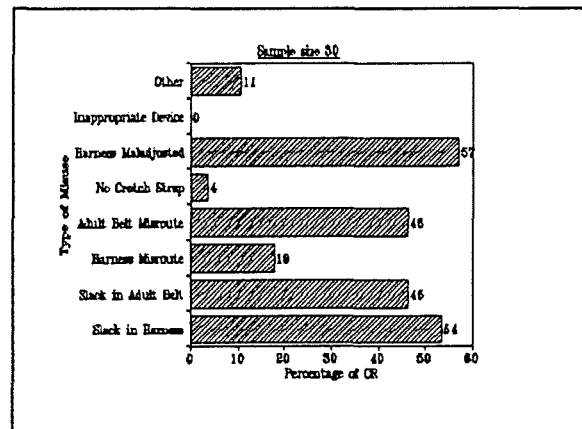


Figure 12.3 Misuse modes in Framed child seats#.

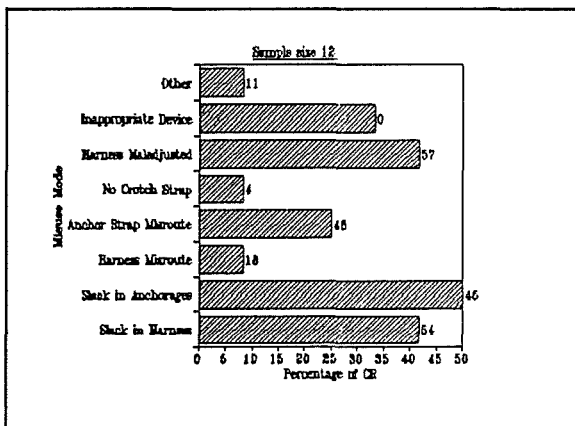


Figure 12.4 Misuse modes in 4 and 2 point child restraints#.

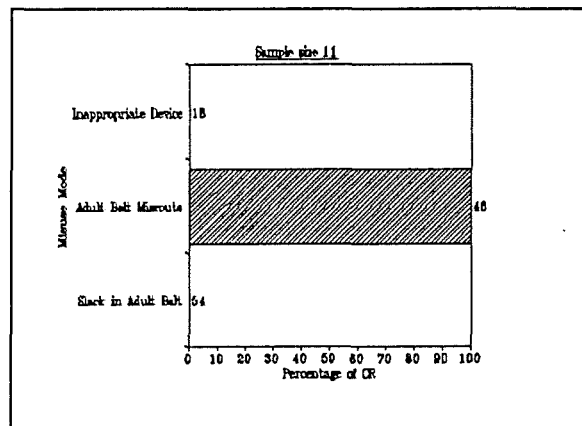


Figure 12.5 Misuse modes in Booster seat and cushions#.

# Note: Misuse levels are shown as percentage of the restraint type that were misused, not of total sample number of restraint type.

Slack in the CR anchorage (either straps or belt) was common in the framed and 4 point seats, but not in the infant carriers. The lack of slack in the infant carriers may be due to the fact that many seat belts are required to be at full extension to fit around the restraint.

A common problem with framed seats was adult belt misroute. The adult seat belt buckle was often located on the CR frame. This is not recommended as the belt can not be fully tightened and the buckle is not structurally sound when loaded in the lateral

direction. One particular framed seat appeared to have a problem with this misuse mode. The Britax 2 Way exhibited a large proportion of seats with adult belt misroute.

Although the sample could be considered to be only child restraint users who were concerned about the fitment, many users appeared surprised when told that their restraints were misused. Many users complained of poor instructions that were supplied with the seats and some who had second hand seats had no instructions at all.

### 12.3 CONCLUSIONS FROM THE MISUSE SAMPLE

Misuse is a serious problem in most types of child restraints. Booster seats and cushion were the only type of restraint that exhibited satisfactory misuse rates. The sample presented in this study was considered to be biased towards misuse, however it is not expected that an unbiased sample would show a misuse rate of below 50%. A common misuse mode was slack in either the restraint harness or anchorages. Framed child seats exhibited a high incidence of adult belt misroute, in particular the adult belt buckle would often lie across part of the seat frame.

Complaints of poor instructions supplied with child seats were common. Ungoverned second hand sales of child restraints should be discouraged as child seats are sold without instructions and can be in poor condition. Greater emphasis on child restraint fitting education is recommended. Parents appeared to have little comprehension of the forces involved in restraining a child in a car impact. Also parents did not have any real understanding of the need for correct child restraint use (e.g. the location of the harness straps on the correct body areas).

### 13 GENERAL DISCUSSION

### 13 GENERAL DISCUSSION

The work conducted and presented in this thesis has comprised three main areas of study:

- The effect of framed child seat design parameters on the injury potential of a child occupant
- The effect of vehicle parameters on the injury potential of a child restrained in a framed child seat
- The effect of some biomechanical factors and seat inclination on the injury potential of a restrained child's head and neck.

Two techniques have been used in the investigations:

- experimental crash simulation using the RSEL impact test rig
- computerised Crash Victim Simulation using MADYMO3D

In addition a brief survey of misuse in framed child seats was conducted.

The methodology and results of each area of study have been presented and discussed in the previous six chapters. This chapter draws together the results. The following is a list and brief summary of the six sections which follow:

- **Experimental Testing vs CVS** - a discussion of the advantages of both experimental simulation and computer modelling and a comparison of the results gained with each

- The Influence of Framed Child Seat Design - general discussion on the results of the studies into various child restraint design parameters
- The Effect of Vehicle Design - a discussion on the extent of the problem of non-uniform vehicle design
- The Difference Between Lap and 3 Point Belt Restrained FCS - observations on the effect of the two anchorage methods
- Child Biomechanics - conclusions drawn from the investigation of some anatomical features on the potential for injury to the restrained child's head and neck
- The Effect of Framed Child Seat Misuse - a discussion of the possible effects of the misuse modes observed in the survey

### 13.1 EXPERIMENTAL TESTING VS CVS

Both the crash simulation techniques used in this investigation have advantages and disadvantages. This section of the thesis discusses the benefits of the two techniques, and the relative accuracies under the following headings:

- Cost
- Simulation time
- Errors
- Modelling assumptions and simplifications
- Versatility

#### 13.1.1 COST

Cost was one of the major reasons for choosing CVS over crash testing. The destructive nature of the test and the high labour

intensity required, make crash testing a costly process. The cost of CVS using MADYMO is limited to the annual licence fee and the labour costs of the software user. Thus the cost of using CVS in this study was less than 10 % of the equivalent tests.

#### 13.1.2 SIMULATION TIME

CVS also has an advantage over testing in terms of speed of simulation. A single test at RSEL requires at least twenty minutes set up time and an hours results gathering even for a series of similar tests. A CVS run of several similar models took around 10 minutes per run. In addition it is generally faster to create a computer model of a particular situation than a physical experimental set up. This is particularly true where large modifications to a test rig are required. Thus it was possible to conduct many more CVS runs in the time available than would have been possible on the test rig.

#### 13.1.3 ERRORS

Experimental error was thought to be the cause of many of the apparently rogue results seen in the test results. When a comparison of results of the two techniques was made (see Section 8.2) some inconsistencies were observed. The inconsistencies were explainable by rogue experimental results, but it was impossible to test this hypothesis without a considerable number of repeat tests. Cost and time implications meant that this was impossible. However, experimental tests have inherent errors. In the case of experimental crash testing the errors lie in some of the following:

- human error in inconsistent set up
- human error in the measurement of results
- inconsistent initial velocity of the sled ( $\pm 2$  kmph)

- slight variations in deceleration pulse
- inconsistency in dummy response

Thus we would expect some errors in the experimental results. Computer simulation is not subject to random errors as observed in tests. A numerical algorithm should always calculate the same result given the same data. However, computer simulation is subject to errors from modelling assumptions and simplifications.

#### 13.1.4 MODELLING ASSUMPTIONS AND SIMPLIFICATIONS

Simplifications are a necessary feature of all crash simulation. A car crash can be modelled almost exactly using an experimental car to car impact, but this incurs a huge cost and requires a large set up time. Therefore simplifications are required to reduce the cost of analysing a restraint system's effectiveness for both experimental and computerised simulations.

A major simplification made in experimental sled testing is in the definition of the vehicle deceleration pulse. The deceleration pulse of a vehicle involved in an actual crash involves six degrees of freedom (three linear and three angular). For a crash test on a rig, this is simplified to a single uniaxial acceleration. In addition the human surrogate (TNO P3 dummy) used in the crash test is a highly simplified model of the human body. The human surrogate is designed primarily to permit repeatable testing rather than as exact representation of the human body.

There are two types of simplifications that are made when using mathematical modelling techniques:

- user defined modelling assumptions
- implicit simplifications of the modelling technique

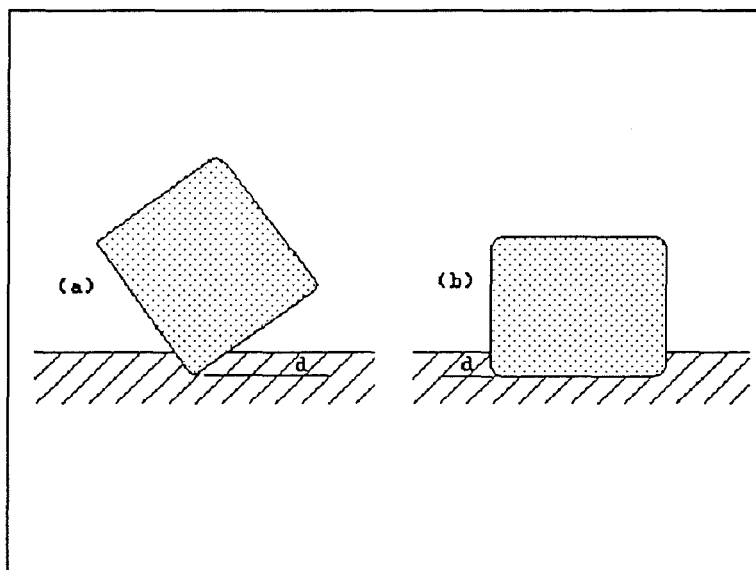


User defined modelling assumptions and simplifications are made when a model is being constructed. It is generally unnecessary to explicitly model all features of a product. Based upon experience and logical deduction the analyst decides which are the features of the product which will be critical in defining its response. When constructing the MADYMO3D model of the surrogate FCS, it was assumed that the frame and feet were very stiff in relation to the other components and could therefore be modelled as one rigid body. However, the modelling of the large plate foot as a rigid body was thought to be one of the contributing factors to the inaccuracy of the results (see Section 8.3) of the simulations of this FCS configuration.

Another source of error when using a technique such as MADYMO is the lack of an initial static balance. When a FCS is placed upon a car seat (or test seat) and the belts fastened, the seat will naturally find a stable static position. This does not occur with a mathematical model. The initial position is user defined. It was not feasible, or considered necessary, to attempt to calculate the initial static position of the system. Thus there was some error in the initial positions. However, no additional initial forces were caused by this simplification, as MADYMO can be set to ignore such features.

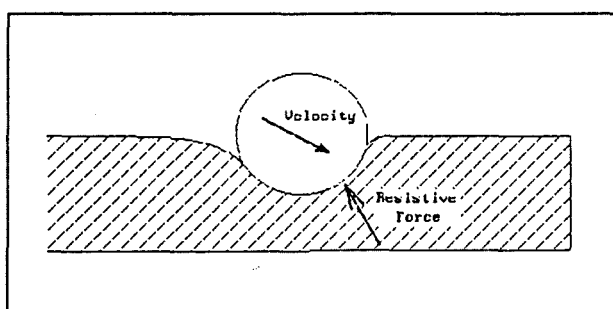
In addition to analyst defined simplifications, there are simplifications inherent in the use of MADYMO. Contact surfaces can only be defined using ellipsoids and flat plates. Thus there are large simplifications required in the definition of complex surfaces, if the number of MADYMO contact surfaces is to be kept to a practical and manageable level.

Contact interactions within MADYMO are also subject to simplifications. Simplifications in the definition of surfaces will lead to inaccuracies in the directions and magnitudes of contact forces. In addition



**Figure 13.1** Illustration of two contacts which would be interpreted identically by MADYMO3D

the contact algorithms in MADYMO take no account of the bearing area of a contact. Figure 13.1 shows two contacts between an ellipse (high order) and a plane which have the same maximum penetration 'd'. In both cases MADYMO3D would calculate the maximum penetration and assign a force interpolated from user provided data. Therefore the force in both cases would be identical. The direction of the forces applied to the bodies is also subject to simplification. MADYMO3D assumes the force to be normal to the plane or ellipsoid surfaces in contact. However, in many contact interactions the force will comprise a second or third component of force.



**Figure 13.2** Contact interaction with non-normal resistive force

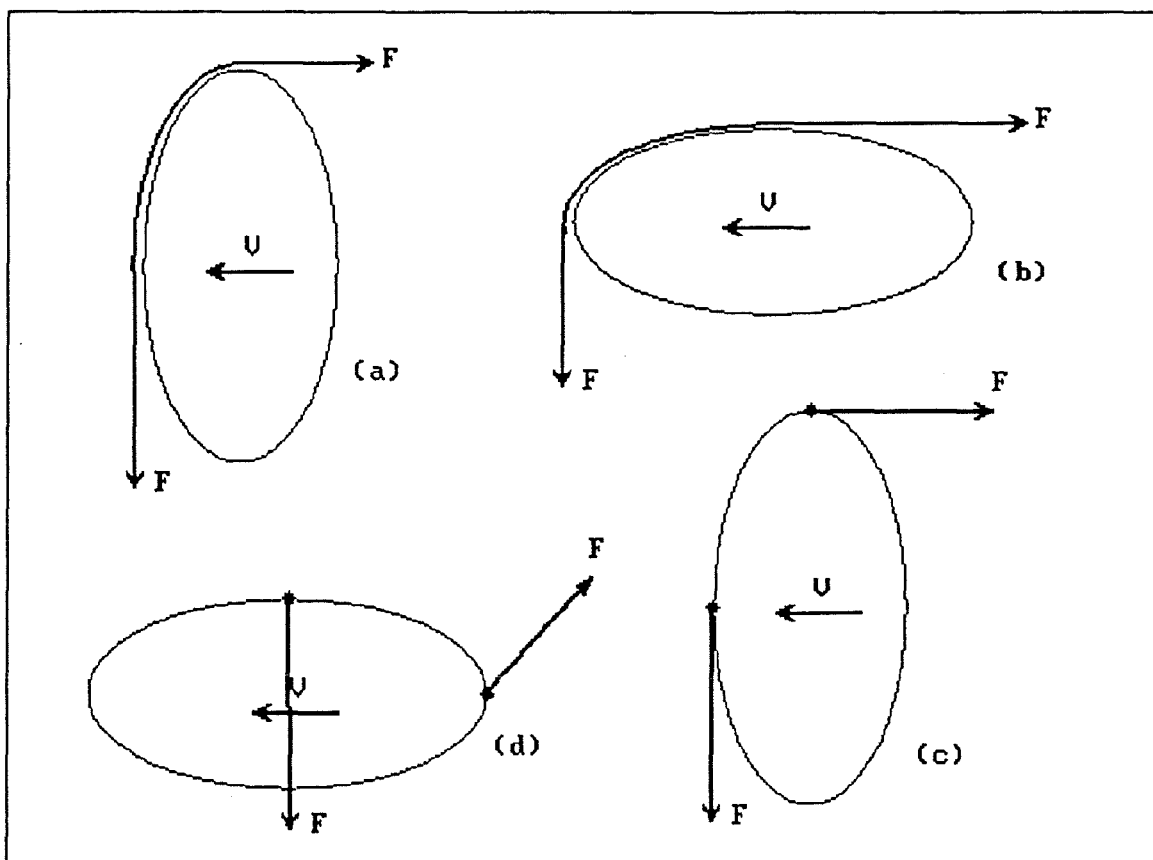
Figure 13.2 illustrates a contact interaction between two bodies which would not have a contact force vector normal to the plane. A round body is penetrating a softer body with both horizontal and vertical

velocity components. The softer body would be crushed vertically

but in addition the material in front of the round body would be crushed. The resulting contact force would therefore have both vertical and horizontal components.

The definition of belt systems in MADYMO also requires some simplifications. Belts are represented by a spring-damper element between two points in a model. The user defines the characteristics of the element allowing a considerable amount of flexibility. However, this belt representation does not operate in the same manner as an actual belt. Figure 13.3 illustrates the restraint on a body from both an actual belt and the equivalent representation in MADYMO. In (a) the body is restrained by the belt due to pressure over the area of belt contact and if the body rotates to position (b) it will also be restrained by the belt. (c) shows a MADYMO representation of the same scenario as (a). The body is restrained by two point forces in the directions of the belt elements. This yields a reasonable representation of the actual restraint method in many scenarios. However (d) illustrates an identical scenario to (b), but where the MADYMO simplification of belt systems would lead to a totally incorrect belt loading. Instead of being restrained by a pressure over the left part of the body as in (b), the body is restrained by the MADYMO belt elements in a totally unrepresentative manner.

Thus both experimental simulation and computerised CVS are both subject to simplifications. Experimental testing uses less simplifications but is subject to other disadvantages as discussed elsewhere in this chapter. Many of the simplifications in mathematical modelling which were discussed are particular to MADYMO3D and similar lumped mass models. Modelling techniques such as dynamic finite element models avoid such simplifications



**Figure 13.3** Illustration of MADYMO belt simplification. (a) real belt restrains body. (b) real belt does not restrain body. (c) MADYMO representation of belt (a) restrains body. (d) MADYMO representation of belt (b) restrains body.

as contact surfaces and interactions can be explicitly modelled.

Modelling assumptions and simplifications are the limiting factor in the use of a technique and the accuracy of the results. At no point in this thesis were the results of the MADYMO3D modelling assumed to be absolute values for child seat performance. The modelling was only used as a comparative tool with which a parametric study could be conducted.

#### 13.1.5 VERSATILITY

A further advantage of CVS over experimental testing is the versatility of the technique. It is possible to simulate many impact scenarios, and vary certain parameters, with computer simulation that are not feasible with experimental tests. eg; a

test which would almost certainly damage an expensive instrumented dummy, or the variation of the mass of a child seat without affecting the centre of gravity or moment of inertia.

The use of computer simulation in this project also allowed the assessment of certain injury parameters which were not possible during experiments. At the time this work was conducted instrumentation was not available to allow the measurement of neck load in a TNO P3 dummy. However it was possible to output this information from the MADYMO3D simulations. Head angular acceleration was also difficult to measure experimentally. An angular accelerometer was not available for direct measurements and to measure the angular component using linear accelerometers would of required extra data acquisition channels and the development of additional analysis software. Thus MADYMO3D provided a more cost effective method of assessing some parameters which were difficult to measure experimentally.

### 13.2 THE INFLUENCE OF FRAMED CHILD SEAT DESIGN

This section discusses the work contained within Chapters 7 and 8 which investigated the effect of various FCS design parameters on the injury potential to the occupant. The following design parameters were examined:

- Variation of adult belt route on FCS frame
- Variation of system centre of gravity via a change in seat shell position
- FCS foot size
- Seat shell inclination
- Effect of a top tether
- Harness stiffness
- Harness slack

- Seating shell stiffness
- FCS mass
- FCS centre of gravity position
- FCS moment of inertia

The effect of each design parameter is discussed in the following subsections. The final subsection provides a general summary.

#### 13.2.1 VARIATION OF ADULT BELT ROUTE ON FCS FRAME

The effect of changes in adult belt route on the frame of the FCS were found to be two-fold. Firstly when the belt was moved forward and/or down the effect was to increase the rotation of the FCS. When the belt was moved backwards and/or up the FCS was allowed greater translational movement. In both cases the head excursion was increased, and in the latter case the chest deceleration was also increased. The optimum position for the belt route would thus be high enough to resist the forward rotation of the seat, whilst keeping the belt angle at as low as possible to reduce translational movement.

#### 13.2.2 VARIATION OF SYSTEM CENTRE OF GRAVITY VIA A CHANGE IN SEAT SHELL POSITION

Changes to seat shell position were shown to affect both head excursion and chest deceleration. If the shell was moved forwards or upwards head excursion was increased and generally chest deceleration was also increased. Thus the optimum position was considered to be as low and far back as possible. The practical limitations on the movement of the shell are the comfort of the occupant and the belt routing. If the seat shell is too low the child can not sit in the normal 'legs down' sitting position and if the shell is too far back there is no room for the adult belt to pass around the frame. The Britax 2-Way, which was selected as

the 'typical' child seat at the beginning of this study, is close to the optimum position. Other child seats are not. The Kangol Super Dreamseat is more forward and some US seats are very much higher. Thus there is a possibility of improvement in performance of some production FCS.

#### 13.2.3 FCS FOOT SIZE

When the foot size of the surrogate FCS to a 450x460 mm plate was consistently shown (in experimental tests) to reduce chest 3ms deceleration in the lap belt restrained FCS surrogate by approximately 30 %. However, this improvement in response was somewhat offset by large increases in head excursion. Head excursion was increased from 419 to 532 mm, close to the ECE R44 limit of 550 mm. Pincemaile et al (1991) has already been mentioned as expressing concern over head excursion limits in the ECE R44 standard. The paper included a graph of available space in some French cars and distances as low as 400 mm were evident. Thus it would seem advisable to reduce the ECE R44 limit, which would mean head excursions as large as those measured with the largest foot would not be acceptable.

#### 13.2.4 SEAT SHELL INCLINATION

Experimental test of both lap and 3 point belt restrained surrogate FCS showed little evidence of improvement in performance from increased seat shell inclination. Although head excursion was reduced (mainly due to a more rearward initial position) chest deceleration was shown to increase. In addition a high head rebound acceleration was noted in many of the test results. It was hypothesised that the high rebound accelerations were a result of increases in neck load. This hypothesis was examined using the MADYMO3D CVS technique with improvement to the

neck representation in the P3 dummy database.

A definite increase in neck load was noted for the reclined seat MADYMO3D simulations when compared with the upright case. An increase of 1 KN over the upright load of 2.8 KN was noted in the resultant force. This was mainly due to increases in the tensile component of force. There is currently no method for determining the likelihood of neck injuries from this data. All injury criteria that exist for children are based upon dummies other than the TNO P3 (see Section 3.3.2). However the results do show a rise in neck load therefore more reclined seating positions should be carefully examined as a potential cause of neck injury.

#### 13.2.5 EFFECT OF A TOP TETHER

Experimental tests to investigate the effect of top tethers were conducted with the surrogate FCS configured with both bar and plate feet. The bar feet configured FCS showed only minimal change in response with and without a top tether, but the FCS configured with a large plate foot exhibited a more marked effect. Head excursion was reduced by over 200 mm with the introduction of a top tether but chest 3 ms deceleration was increased from 40 g to 65.5 g. This change in response due to the top tether effectively nullified the effects of the foot area increase.

It was not possible to model the large foot case with a reasonable degree of accuracy (see section above on foot size), but a MADYMO3D model of the bar foot configured, lap belt and top tether restrained FCS showed a distinct improvement in performance over the lap belt only case. Chest 3ms deceleration was reduced by 16% and head excursion by 28%. The difference



between the test and MADYMO3D model results was considered to be due to flexion of the bar on the surrogate FCS to which the top tether was attached, and take-up in the belt threading, neither of which allowed the tether to tighten sufficiently.

The MADYMO3D CVS provides some indication of the possible advantages of a more highly restrained FCS. A top tether was shown to considerably improve FCS performance and it is more easily tightened than the 3 point inertia belt (see chapter 9 for problems observed with inertia reel belts in real car bodies). However, there are disadvantages of the top tether. It requires a dedicated anchor for the tether strap in each vehicle that the user requires the FCS to be fitted and the fitting of top tethers has been made more difficult with the increase in numbers of the hatch-back car. There is no solid parcel shelf on which to mount the strap and the alternative is a long strap reaching back into the vehicle's luggage space. In addition misuse of top tethers has been shown to be a major problem in the USA, in particular the non-use of such straps (see Section 4.2.2.1).

Thus there are many valid objections to the introduction of the top tether as a common anchorage method. A more preferable solution to the problem of solid anchorages for FCS may lie in the ISOFIX concept. ISOFIX is discussed in more detail in Section 13.3.7.

#### **13.2.6 HARNESS STIFFNESS**

The effect of harness stiffness was evaluated using MADYMO3D CVS. Reductions in harness webbing stiffness from that of a typical harness webbing was shown to induce excessive head excursions whilst reducing chest deceleration. Increasing the webbing

stiffness reduced the head excursion slightly and increased chest 3ms deceleration by a similar order. Thus there appears to be little opportunity for improvements over the current harness stiffness. Although the energy absorption characteristics of such webbing could feasibly be improved to reduce decelerations whilst keeping head excursion to a reasonable level. This was not considered in this study.

#### 13.2.7 HARNESS SLACK

Slack in the harness was examined using the MADYMO3D CVS technique. The simulation with the standard measured value for slack in the harness (29 mm in the shoulder belt) was re-run with the slack doubled and removed. With increased slack the expected result was obtained. Both excursion and chest 3ms deceleration was increased. Excursion was increased as a direct result of the extra webbing. The deceleration was increased due to the higher relative velocities induced between occupant and vehicle when the slack is taken up in the harness.

When slack was reduced to zero, the chest deceleration and head excursion were reduced. But neck load and HIC were increased. No firm conclusions can be drawn from this results, but the more solid anchorage of the torso appears to increase the rotational acceleration and velocity of the head and therefore increases neck load and HIC. In reality the sometimes thick clothing on a child and maladjustment mean that it is unlikely for a child to be very tightly restrained, ie; no slack. And even if a torso is tightly restrained, its flexibility may allow more torso movement than modelled in this simulation, but this effect should be given closer scrutiny.

#### 13.2.8 SEATING SHELL STIFFNESS

The shell stiffness was investigated in terms of the contacts with the occupant. When the stiffness of the contact interactions in the MADYMO3D model was varied over a -75% to +400% range around the standard typical value, the head excursion and chest deceleration were only altered by approximately 5%. Therefore the restraint of the occupant can be seen to be mainly due to the harness, and the shell stiffness plays a minor role.

#### 13.2.9 FCS MASS

The mass of the typical production framed child seat (Britax 2-Way) was 5.7 Kg and the sample of FCS weighed, varied over a range of approximately 4 to 9.5 Kg. The surrogate FCS, which was the basis of the MADYMO CVS models, had a mass of 7.5 Kg. Therefore it was appropriate to test the effect of FCS mass by varying the surrogate FCS model's mass by  $\pm 3$  Kg, which encompassed the range of current FCS designs.

The simulations predicted that for both the lap belt and 3 point belt restrained surrogate FCS an increasing mass resulted in a general increase in the IPI. However, over the 6 Kg mass variation the change in head excursion was approximately 2% and chest 3ms deceleration 14%. Therefore it can be recommended that mass of FCS should be minimised, but it need not be a critical specification for the FCS designer.

A minimised FCS mass has the additional advantage of being more easily carried by the user (parent or guardian).

#### 13.2.10 FCS CENTRE OF GRAVITY POSITION

The centre of gravity position of the surrogate FCS was varied in the vertical and horizontal planes by  $\pm 50\text{mm}$  in the MADYMO3D model. The model predicted that horizontal (forward back) movement has little effect. Vertical movement had a greater effect. The FCS with a higher centre of gravity was predicted to increase most of the IPI examined. Variations were small (all bar HIC under 7%), but it is clear that a lower centre of gravity position is preferable.

#### 13.2.11 FCS MOMENT OF INERTIA

The moment of inertia of an element in MADYMO3D is explicitly defined in the input deck. Therefore it was a simple task to vary this value over a range and assess the effect on performance. For both the lap and 3 point restrained surrogate FCS, the CVS predicted a change in chest 3ms deceleration of under 6% and a head excursion change of 2 % for a range of moment of inertia from -75% to +400% of the surrogate's value. Therefore moment of inertia can not be considered to be a governing factor of FCS performance.

#### 13.2.12 SUMMARY OF THE EFFECT OF FCS DESIGN PARAMETERS

None of the design parameters examined was shown to be a critical governing factor on FCS performance. The parameter which came closest to this, was perhaps adult belt route position. On a typical production FCS changes to belt route were shown, by experiment, to drastically effect the structural integrity of the seat. This was not surprising as the FCS was being used in ways for which it was not designed. The MADYMO3D CVS models also predicted an overturning of the surrogate FCS when the belt was moved far forward and down.

Foot size was shown, by experiment, to drastically reduce chest deceleration. But increases to head excursion occurred which may make such designs impractical, particularly in modern compact cars with smaller occupant spaces.

Other design parameters had a less severe effect, altering the various Injury Potential Indicators by a few percent or so. However, if several of these parameters were altered from the typical values used in these models and experiments a more dramatic effect on performance might be expected. Simulations with various combinations of design parameters to test this theory were not conducted.

The work in this area has high-lighted some particular areas of concern. The most important of which is the possible effect on neck load of a reclined seating position. Head rebound acceleration was observed to increase in tests and MADYMO3D simulations predicted an increase in neck load for more reclined positions. The limitations on the modelling technique used are such that further conclusions can not be drawn on the likely injury levels, but further work should be conducted.

### 13.3 THE EFFECT OF VEHICLE DESIGN

Experimental tests were conducted, using the rear halves of three car bodies, in an attempt to quantify differences in the performance of FCS when placed in real vehicles as opposed to laboratory test seats. During the set up of the tests it was noted that it was considerably more difficult to tighten the adult belt around the surrogate FCS in the car bodies than in the test seat. This difficulty was due to reduced accessibility and the shaping and stiffness of the vehicle seats. Additionally the

inertia reel seat belt, which was used for half of the tests, is not capable of locking and it is therefore impossible to obtain a tight fit.

The difficulty in obtaining a tight anchorage for the surrogate FCS was reflected in the high head excursions measured in the vehicles (approximately 100 mm (20 %) greater. It was not known whether this was the only reason for the high excursions, there may of been other factors contributing to the change in performance. It was not feasible to isolate design parameters in the car bodies in order to test the effect of each. Therefore, MADYMO3D CVS was used to investigate this area.

Six vehicle design features were examined using the CVS technique:

- Adult belt slack (due to the use of an inertia reel belt)
- Adult belt anchorage position
- Adult belt stiffness
- Seat squab stiffness
- Seat squab depth
- Vehicle deceleration pulse (affected partly by vehicle design)

The main conclusions drawn from this work is discussed in the following sections and is summarised in Section 13.3.7.

#### 13.3.1 ADULT BELT SLACK

Slack in the diagonal section of the 3 point belt representation in the MADYMO3D model was varied, in an investigation designed to quantify the effects of such a variation. This was also intended as a initial study into the effect of the slack observed in the set up of the car body tests where the surrogate FCS was

restrained by an inertia reel belt. Three levels of slack in the diagonal were modelled; 0, 29 mm and 60 mm. 29 mm was as introduced in all the 3 point tests conducted for this thesis. This is not a requirement of a FCS test conducted to either the ECE R44 or BS 3254:Part 2:1988 standards, but is included in the new issue of the British standard (BS 3254:Part 2:1992).

Slack was predicted to linearly affect the IPI considered over the tested range. A  $\pm 20\%$  variation in chest 3ms deceleration was observed for a +31 mm -29 mm variation in diagonal slack, and head excursion varied by approximately  $\pm 3\%$  over the same range. The increase in head excursion for a diagonal slack of 60 mm was not of the same order as that observed in the car body tests. However, there are some major differences in the car design and adult belt that were not considered in these MADYMO3D models. In particular:

- The reel out of the inertia reel belt was not explicitly modelled. It could feasibly cause greater slack in the belt than the 50 mm slack included in the model.
- No slippage between diagonal and lap sections of the belt was modelled. This is not thought to occur during an impact test, due to the nature of the belt route on the surrogate FCS, but pre-test slippage would re-distribute the initial slack in the belt.
- No other vehicle design parameters were considered e.g. squab depth or loading from flexing backrest.

Thus the model shows a significant negative effect of belt slack, but cannot in itself explain the car body results as there were considerable differences between model and test.

### 13.3.2 ADULT BELT ANCHORAGE POSITION

The effect of a more forward lap belt anchorage position, as observed in the seat belts of many modern vehicles, was investigated using MADYMO CVS. The CVS predicted considerable increases in head excursion and chest 3ms deceleration for the more forward positions (up to 40 % for lap belt restrained case).

A more forward anchorage position has been used in the outboard lap anchorage of inertia reel belts in many modern vehicles, in an attempt to improve the performance of the seat belt for adult occupants. Fitting of FCS in such vehicles has been observed to be made more difficult by this design change. The CVS conducted for this thesis predict severe degradation in FCS performance when such adult belts are used as anchorages. Thus there is a clear conflict between the adult requirements for a seat belt and the requirements for the anchorage of FCS.

It may be possible to resolve these differences by re-designing FCS. However, not all vehicles utilise the more forward adult anchorage and there would therefore be considerable design problems in creating a FCS to utilise both belt types.

The only satisfactory solution to the conflict between adult and FCS use of the adult seat belt is for child seats not to be anchored by the adult seat belt, but by dedicated anchorages. The dedicated anchorage would have to be easy to use, to avoid misuse, and available in all vehicles to avoid non-use. This is the ISOFIX concept (discussed in Section 13.3.7).



### 13.3.3 ADULT BELT STIFFNESS

The CVS conducted to investigate the effect of changes to adult belt stiffness showed little advantage in such changes. A reduction in stiffness induced excessive head excursions and increases in stiffness of 400% only reduced excursions by 5%.

It would of course be impossible to apply such design changes in any event. There would be a conflict with the requirements for adult restraint.

### 13.3.4 SEAT SQUAB STIFFNESS

Seat squab stiffness was predicted by MADYMO3D simulations to have a minor effect on FCS performance. 400% changes in seat squab stiffness yielded changes of under 4% in chest 3ms deceleration and head excursion.

It should be remembered that MADYMO CVS of changing FCS foot size, failed to simulate the changes in performance observed in the experimental work. Thus there was a question over the accuracy of the representation of the foot-squab contact in the MADYMO models.

It is physically possible for a person to apply enough weight to a bar foot configured FCS on the ECE R44 test seat, to compress the squab fully. This force (approximately 300 N) is considerably lower than the forces required to restrain a FCS (2.5 - 6 kN measured in belt loads), thus we might not expect the squab stiffness to have a significant effect on performance.

#### 13.3.5 SEAT SQUAB DEPTH

The FCS was observed to interact with the seat during both experimental and CVS impacts. The fact that the FCS appeared to be subject to some restraint from the seat and the seat squab was apparently applying little force to the FCS (squab stiffness had little effect) meant that it must be the seat pan which was restraining the FCS movement. Seat squab depth could therefore be expected to affect the FCS performance.

MADYMO3D CVS of the surrogate FCS were conducted for seat squabs of varying depth (100 - 180 mm. 140 mm is standard depth for test seat). The lap belt restrained FCS was predicted to be affected to a larger extent than the 3 point case. Head excursion increased by approximately 10% for a 40 mm squab depth increase. And vice versa for a decrease. The greater the squab depth the more the FCS could move, and thus the greater the head excursion. All the other IPI increased as squab depth increased, and there were no significant increases as squab depth was decreased. Thus the results appear to show that the thinner the squab the greater the improvement in FCS performance.

Vehicle seat squab thickness varies between vehicle models and through the cross-section of most seats. A car rear seat is generally thinner at the centre where the drive shaft tunnel is located. Thus there could be considered to be some concern over the performance of FCS when fitted in various vehicles.

#### 13.3.6 VEHICLE DECELERATION PULSE

The vehicle deceleration pulse is not a primary design feature of most vehicles. The deceleration of a vehicle in a crash is governed by the object which it strikes and its structural

design. A vehicle is generally designed to preserve the occupant compartment when involved in an impact of given speed and direction as defined in standards (currently 30 mph frontal impact is typical). The manner in which it decelerates is not tested in the standards.

The MADYMO3D CVS which were conducted to investigate this area predicted that the restrained child was influenced to a greater extent by deceleration spikes occurring at a later stage in the vehicle's deceleration. In addition the occupant was affected more by a deceleration spike which altered the total velocity change of the vehicle rather than a temporary local velocity change.

The former finding can be explained by considering the position of the occupant at the latter stages of vehicle deceleration. The occupant is forward in the FCS, all belt slack is taken up and there is a direct load path between occupant and vehicle. Therefore any sudden changes to the vehicle's deceleration are directly transferred to the occupant. In the early stages of deceleration the occupant is in free flight (before slack is taken up) and therefore changes to vehicle deceleration have less effect.

The latter finding is more simply explained. Alterations in the total velocity change of vehicle and occupant must mean alterations in the required kinetic energy change of the occupant. Kinetic energy change of the occupant is achieved by forces applied on the occupant by the FCS harness. Thus the accelerations of the occupant will be affected by a greater extent by overall velocity changes rather than local ones.

It is the former result which is of more interest to the vehicle designer. The overall velocity change is dependant upon the accident scenario, but it may be possible to alter the manner in which the vehicle decelerates . The results of the work here are in agreement with those of Lundell (1984), who conducted similar work for adults, and shows that it is preferable to cause deceleration spikes earlier in the total pulse rather than towards the end.

#### 13.3.7 SUMMARY OF EFFECTS OF VEHICLE DESIGN

The results of the investigations in this area show that FCS performance is affected by some vehicle design parameters. In particular variations of belt anchorage position and squab thickness were predicted, by MADYMO3D modelling, to induce significant changes to FCS performance. This would imply that the concept of a "universal" FCS anchored by the adult seat belt is extremely difficult to achieve. There is therefore some question over the performance of FCS in current vehicles.

The results of the investigation into the effect of belt stiffness, showed little benefit from altering the stiffness of these anchorage straps. However, the results did show that FCS performance improves, as we would expect, with a stiffer anchorage.

An anchorage method which would overcome the problems of misuse, vehicle design differences and provide a stiff anchor is the ISOFIX concept. The ISOFIX concept comprises a dedicated set of anchorages which would be available in all new cars for the anchorage of child seats. The fixing system would be uniform throughout all vehicle makes and models and ideally isolate the

child seat from the vehicle design (no interaction with vehicle seat). The design will be simple to use, to minimise misuse and available for the anchorage of all child seats ie; infant carriers, toddler seats, booster seats, shields etc. This concept is still in early stages of development and it is not known whether the concept will be introduced. The author of this thesis strongly recommends the introduction of such an anchorage system.

#### 13.4 THE DIFFERENCE BETWEEN LAP AND 3 POINT BELT RESTRAINED FCS

The work conducted for this thesis has considered framed child seats anchored by two restraint methods, adult lap belts and adult 3 point belts. The work has highlighted two major differences between the anchorage methods:

- The lower sensitivity of 3 point belt restrained FCS to changes in seat or vehicle design parameters
- The difficulty tightening the 3 point belt (particularly inertia reels) when fitting the FCS.

The 3 point belt restrained FCS was observed, in both experimental and MADYMO3D computer simulations, to consistently be less sensitive to changes in either FCS design (e.g. foot size or shell position variations) or vehicle design. This was due to the rotational restraint of the 3 point diagonal strap. Most of the design parameter variations resulted in changes to the rotation of the FCS. The lap belt restrained FCS has no upper strap to restrain rotation (unless fitted with a top tether) and thus design changes which increased the couple on the FCS, resulted in increases in rotation. The diagonal strap of the 3 point belt was observed to resist such movement, therefore making the 3 point restrained FCS less sensitive to such changes.

The lower sensitivity of such an anchorage system should make it

more suitable as a restraint for FCS. Changes in seat and belt design in different vehicles, would not result in dramatic changes to a FCS's performance and thus the truly universal FCS would be more attainable. However, there were considerable problems noted in the fitting of FCS with static 3 point and inertia reel 4 point belts.

The addition of a third strap, which requires loading in the opposite direction to the lap straps, means the 3 point static belt is more difficult to fit tightly than a lap belt. And an inertia reel belt is almost impossible to tightly fit, because the reel cannot be locked and will continually provide slack. The webbing lock on production FCS is supposed to stop slack from inertia belts, being transferred into the lap section. However, many of the webbing locks on FCSs tested at RSEL were observed to be ineffectual. The slack induced from inertia reel belts was thought to be a major contributor to the poor FCS performance observed in the car body tests. Inertia reel lap and diagonal belt restrained FCSs were observed to perform significantly worse than lap belt restrained FCSs.

There are solutions to the problems of fitting universal child seats into non-universally designed vehicles. Two of which are:

- Vehicle manufacturers provide information on the appropriate child seat for use in their vehicles. The seats would have to be tested in the vehicles and the manufacturer would define which seat and seat belt should be used.
- Universal dedicated anchorages for the fitting of child seats in multiple seating positions within all vehicles.

The former solution has the advantage that no modifications to existing vehicles or child seats may be necessary. In addition it

would be possible to 'retro fit' the solution, i.e. recommend child seats for old vehicles. However, it may not be possible to identify an appropriate child seat and vehicle combination for all vehicles and the solution does not help reduce misuse of child seats. The implementation of such a solution was attempted through European law, but it was rejected because it was thought to conflict with the free trade philosophy of the EEC.

Universal dedicated anchorages would provide an anchorage method for child seats in all vehicles. They could be designed to isolate the child seat performance from the vehicle design and reduce misuse. Such an anchorage concept is the ISOFIX concept discussed in the last section. The major drawback of the dedicated anchorage concept is that it probably could not be fitted to old vehicles and it will take a considerable period of time to be implemented.

A combination of the two solutions discussed above would provide the ideal solution. Old vehicles and existing models would use recommended child seats with existing anchorage methods. Future models would utilise the dedicated anchorage method.

### 13.5 CHILD BIOMECHANICS

The child biomechanics work conducted for this thesis mainly comprised an investigation into some factors which may affect neck injury levels. The existing MADYMO3D TNO P3 database was shown to be inaccurate as a representation of the dummy neck. An improved dummy neck representation was developed and introduced. The improved MADYMO3D TNO P3 database was used in an investigation of the effects of three biomechanical factors:

- Chin-chest contact

- Head mass
- Fulcrum for neck bending

In addition the effect of seat inclination was investigated as discussed above.

There were recognised limitations on the conclusions which could be drawn on neck injury levels. The MADYMO3D model was based upon the TNO P3 dummy rather than an actual human neck. Thus the dynamic response and subsequent loads calculated were based upon the dummy and there was no available information with which to correlate the dummy response to a human child response. The model could therefore only be used to identify possible areas of concern for further investigation.

#### 13.5.1 CHIN-CHEST CONTACT

Considerable development time was required in order to model the chin-chest contact of a TNO P3 dummy. The existing upper torso geometric representation in MADYMO3D was inaccurate and the addition of other contact surfaces was required. Several combinations of ellipsoids were tried until a suitable method was identified.

The contact interaction force-penetration contact was taken from that defined in a MADYMO2D model of the P3/4 dummy. Computer runs were conducted with; no chin-chest contact, chin-chest contact and a half stiffness chin-chest contact.

The chin-chest contact was shown to considerably alter the predicted neck load and head angular acceleration. The stiffer the chin-chest contact, the higher the resultant neck load (the increases in resultant neck load were up to 50 % of the original



load). The force from the chin-chest contact was directed backwards on the chin which caused both increased shear and tension in the neck. Without chin-chest contact, the force in the neck is almost exclusively tensile due to the inertial load imposed by the head.

The results show the importance of the chin-chest contact to the loads induced in the child's neck. Thus the stiffness of a dummy's chest should be considered a critical factor in defining the biofidelity of the neck response. Further conclusions on the injury level induced by the loads observed are impossible. There is a lack of biomechanical injury data available for all humans, but in particular children and the TNO P3 dummy (see Section 3.3.2).

#### 13.5.2 HEAD MASS

The tensile force induced by the inertial load of the head was the main component of the neck load predicted by the MADYMO3D simulations discussed in the last section. During the initial phase of occupant motion, the head moves in an arc relative to the torso and is restrained by the neck. The force required to restrain a body on a circular path (centripetal force) is in proportion to the body's mass and the velocity squared. Thus we would expect the neck load predicted in the initial stages of an impact simulation to be proportional to the head mass. However, the head is additionally loaded by the chin-chest contact and thus the load on the neck is not purely due to centripetal force. It was therefore judged important to assess the effect of a change in head mass on neck load.

Three head masses were considered. The 5th, 50th and 95th

percentiles (The TNO P3 dummy on which the MADYMO3D database is based is a 50th percentile). MADYMO3D simulations were conducted with and without the chin-chest contact.

The simulations which did not include the chin-chest contact predicted increasing neck load with head mass. The centripetal force applied by the neck to the head, increased proportionately with head mass. However, the simulations which included chin-chest contact exhibited a slight decrease of peak neck load with head mass. The peak neck load occurred when the head was loaded by the chest contact. The 5th percentile head was accelerated to a higher velocity, by the chin-chest contact force, than the heads of higher mass. Therefore the neck was required to impose a higher force to restrain the movement of the 5th percentile head than the 50th or 95th percentiles.

It was shown that it is not necessarily the case that a child whose neck is relatively undeveloped, compared to the development of its head (95th percentile head on 50th percentile neck), is under any greater chance of injury than a 'normally' developed child. It is dependant upon the chin-chest contact stiffness. If the chest contact stiffness is low, the centripetal force may govern the neck load (i.e. high head mass high load). However, if the chin-chest stiffness is high, the contact force may govern the neck load. The model used was based upon the TNO P3 dummy, thus it would be invalid to attempt form any further conclusions based upon these results.

### 13.5.3 FULCRUM FOR BENDING

The fulcrum for normal bending in a young child's neck is higher (around the C3 level) than in the developed adult where it is in the C7 region. The effect of a change in the fulcrum for bending was examined by locking the joints in the MADYMO3D neck model below the C3 joint.

The predicted rotational head accelerations and neck loads were not greatly affected by this change. The rotational head acceleration pulse was slightly altered in shape but not in magnitude and the peak resultant neck load was increased by around 10%. The most significant affect on neck load was an increase in the shear force, caused by a change in head angle and velocity when contacting the chest.

Increases in shear load would be likely to contribute to cervical joint dislocations. Thus it may be the case that the child's state of physical development (location of fulcrum for bending) would affect the injury potential.

### 13.5.4 SUMMARY OF CHILD BIOMECHANICS INVESTIGATION

The conclusions drawn in this part of the thesis were limited by a lack of knowledge of child biomechanics and response to impact. The neck model used in this study was based upon a dummy rather than a human for this reason, and there was no injury tolerance data with which the results could be compared. However, some areas of interest and possible concern have been identified.

The neck loads predicted by the MADYMO3D models were shown to be dependant upon the stiffness of the chin-chest contact. In particular the shear force in the neck was increased when this

contact interaction was included in the model.

Head mass was shown to affect the tensile force in the neck, due to inertial loading, and to alter the response to chest contact. In addition the location of the fulcrum for neck bending was shown to affect the head response and subsequent neck load due to chin-chest contact.

### 13.6 THE EFFECT OF FRAMED CHILD SEAT MISUSE

The effect of the adult belt route on a 'typical' production FCS was examined and found to cause a loss in structural integrity of the seat. Large deformations of the frame were caused and in one case the seat 'flipped' over the restraining adult lap belt. Because of the frame deformations the results could not be interpreted in terms of effect of belt position, but do give an idea of the possible effects of misuse.

Slack in the harness and adult belt were two of the most common misuse modes observed in the sample of child seats discussed in Chapter 12. This is perhaps not surprising in the view of the difficulties encountered in tightening the seat belts in the car body tests discussed above. The effect of such slack has been discussed above, and mainly comprises increased chest 3ms decelerations and head excursions.

## 14 CONCLUSIONS

## 14 CONCLUSIONS

This thesis has been concerned with the effects of:

- child seat design parameters,
- vehicle design parameters,
- and some biomechanical factors,

on the injury potential of a restrained child occupant of a car impact. The only method of restraint which has been considered is the Framed Child Seat (FCS). The conclusions from these sections of the investigation will be presented in three sections.

The FCS has been studied in both the lap belt restrained and 3 point belt restrained configurations and conclusions are presented on the effect of the anchorage method.

Two tools have been used in the investigation:

- Experimental crash simulation using the RSEL test rig at Middlesex University.
- MADYMO3D computerised crash victim simulation.

The use of these tools has highlighted the advantages and disadvantages of each and thus further conclusions are presented on this topic.

### 14.1 CONCLUSIONS ON FCS DESIGN PARAMETERS

No single FCS design parameter was found to govern the performance of the seat. Most of the parameters examined had some effect on performance, but some effects were too small to be of major concern.

The belt route around the FCS frame was found to structurally compromise the performance of a typical production FCS, if it was altered from the manufacturers recommended position. On the

surrogate FCS the belt route was shown to have an effect on both translational and rotational movement of the seat. There is some possible scope for improvement of FCS performance by the alteration of this parameter.

Footprint area of the FCS on the vehicle seat was shown to dramatically reduce chest 3ms decelerations (a reduction of 33% for the largest foot over the smallest). However, head excursions were increased to close to the ECE R44 limit, which by some is considered to be too high. Thus footprint area may not provide a suitable method for reducing injury to child occupants.

Seat shell inclination was shown to have little effect on head excursion or chest 3ms deceleration, but did have a significant affect on neck loads. An improved MADYMO3D neck representation was incorporated into the standard P3 database and models run with more reclined seating positions exhibited up to 36% greater neck axial loads. It is not certain whether the model results reflect what would occur in human occupants, but it does give cause for concern.

The centre of gravity of the FCS was altered experimentally by a movement of seating shell and in CVS by a direct change in nominal position. In both cases the optimum position was shown to be as low and rearward as possible.

Top tethers were shown to reduce head excursions and generally reduce chest decelerations by providing a more rigid restraint of the FCS. However, the experience of misuse of such tethers in the USA means that the extensive introduction of tethers in the UK can not be recommended.

FCS mass was shown to affect the performance of the surrogate FCS, but not to such an extent that it should be a governing consideration of the FCS designer. However a minimised mass is recommended, based upon both the effect on performance and the convenience of the user.

Neither moment of inertia or seat shell stiffness were shown to have a significant effect on performance and harness stiffness was found to be at approximately the optimum level.

#### 14.2 CONCLUSIONS ON VEHICLE DESIGN PARAMETERS

A small number of tests were conducted with actual car bodies bolted onto the test sled. Difficulty was encountered in the set-up in achieving a tight anchorage due to the design on the adult seat belt and the stiffness and shape of the car seats. This was reflected in the test results which exhibited excessive head excursions. There should be considerable concern over the fitting and performance of FCS in real cars when experienced researchers can not achieve a satisfactory anchorage.

MADYMO3D CVS was used to investigate the effect of specific vehicle design parameters. Belt anchorage location was one of those parameters. The more forward outboard anchorage of many modern cars was modelled and shown to considerably reduce FCS performance. Five anchorage locations in total were considered for both the lap belt and 3 point belt restrained FCS. The optimum position was shown to be far back and above the current typical positions. Thus there is a conflict between the adult requirements of the seat belt (forward to reduce submarining) and the requirements for anchoring FCS. The only way of resolving this conflict is to provide dedicated anchorages for child seats,



such as the ISOFIX concept.

Seat squab stiffness was shown to have minimal effect on FCS performance, but squab depth was shown to have a marked affect. Deeper squabs resulted in greater rotation and translational movement of the FCS. Thus a thinner squab is recommended. This conclusion is in keeping with the more general finding that the FCS requires as rigid an anchorage as possible.

The effect of the vehicle deceleration pulse was examined by altering the input pulse to the MADYMO3D model. The occupant's injury potential was found to be more susceptible to alterations in overall vehicle velocity change as opposed to the manner in which it decelerated. However, larger changes in performance were noted when the latter stages of vehicle deceleration were varied. These results are similar to work previously conducted for lap belt restrained adult occupants and suggests that vehicles should be designed such that rapid deceleration occurs at the earlier stages of an impact.

#### 14.3 CONCLUSIONS ON BIOMECHANICAL FACTORS

The MADYMO3D TNO P3 database's representation of the dummy neck was shown to be inaccurate and an improved neck model was developed. The neck loads observed in an impact simulation of a lap belt restrained surrogate FCS were shown to be highly dependent upon the stiffness of the chin-chest contact. Thus it is strongly recommended that in any future neck injury biomechanical studies, the chin-chest contact is given equal importance to the neck representation.

The conclusions drawn from this work are subject to limitations.

The MADYMO3D model was based upon the TNO P3 dummy rather than an actual human neck. Thus the dynamic response and subsequent loads calculated were based upon the dummy. No information was available with which to correlate the dummy response to a human response, thus the model could therefore only be used to identify possible areas of concern for future investigation.

Increases in head mass were shown to increase neck axial load due to centripetal loading. However, when chin-chest contact occurred the models run with a higher head mass exhibited slightly lower neck loads. Thus it may not necessarily be the case that children with a relatively high head mass will be more susceptible to neck injury. It will be dependent upon the chin-chest contact and loading conditions.

The effect of the location of the fulcrum for neck flexion was also investigated using the improved MADYMO3D neck model. Higher fulcrum are evident in the normal bending modes of young children. The neck model with a higher fulcrum for bending was shown to exhibit slightly higher neck loads and a change in direction of load. The higher fulcrum leads to changes in the loading direction from the chin-chest contact which resulted in a higher shear component of neck load. Thus the state of development of the child's neck may affect the injury potential.

#### 14.4 CONCLUSIONS ON ANCHORAGE METHOD

The lap belt restrained FCS was shown to be more sensitive to changes in either FCS or vehicle design than the three point belt. The diagonal strap of the three point belt, restrained rotational movement which was often increased by such changes. However, the 3 point inertia reel belt, which is fitted in most

modern vehicles, was found to be difficult to tighten in the car body tests. In addition such belts often have the more forward anchorage point, discussed above, which reduces FCS performance. Thus neither the lap or three point belts can be recommended without qualification. The solution to the problem is either the introduction of dedicated child seat anchorages or the specification of particular child seats for particular cars and seat positions.

#### 14.5 CONCLUSIONS ON CRASH SIMULATION METHOD

MADYMO3D crash victim simulation provided an efficient tool for the investigations presented in this thesis. It was both more cost and time effective than equivalent experimental tests. However, the technique is subject to significant modelling simplifications which limit the applicability of the technique. In particular the changes in performance observed for a FCS configured with a large foot were not predicted by the MADYMO3D model.

The major limitations of the technique are caused by the lack of explicit modelling of structures. The FCS in the models presented here was effectively modelled as a rigid structure. In reality the surrogate FCS was susceptible to both elastic and plastic deformation.

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## APPENDIX A

## APPENDIX A

### DESIGN OF THE SURROGATE CRS

The design of the surrogate framed child seat was based on dimensions taken from the typical production seat used in phase 1 and can be viewed in Drawings A.1 and A.2. A standard production model seat shell was used in conjunction with this frame.

The seat parameter variations were chosen to yield a seat that could feasibly be used in a standard automobile. Thus some variations may not be considered by some to be large enough to gain a noticeable difference in results.

The belt types chosen for use with this CRS were; (a) Lap belt surrogates, two lengths of standard webbing attached to both anchorage and seat with standard double slotted mounting brackets. This allowed greater movement of the shell and belt route. (b) Static Lap and Diagonal Belt with 1" slack. A surrogate for this type of belt was not thought appropriate. However the use of this belt did restrict the movement of the shell due to the webbing routing through the seat. Variation of the route for this belt was difficult and thus a surrogate belt was used for some tests.

The methods of parameter variation for the various phases are itemised below;

C of G Variations in CRS centre of gravity were achieved with a variation in shell position (positions a to i, Drawing A.3). Table A.1 includes the C of G measurements.

Foot Type Foot types and areas were varied with the simple bolting of a foot to the original bar positions.

Reclining Reclining of the seat was achieved with additional holes in the side plates, allowing the seat to be swung into required position (see Drawing A.3). NB: Reclining about base for lap belt position (g) was not possible due to spatial difficulties, thus position (i) was used for this test.

Belt Route Changes in belt route (Phase 5 and 7) were only practical for bolted belt surrogates. Various holes were placed in the side plates for this purpose.

Webbing Clamping Lap belt Webbing clamping (Phase 6) was possible with the addition of two bolted sections below the lap belt slots in the side plate.

A list of the CRS's various masses and C of Gs appears as Table A.1.

TABLE A.1

CRS MASS AND CENTRE OF GRAVITY FOR EACH TEST CONFIGURATION

The centre of gravity for each CRS is stated for the seat only with no dummy in position. This is to give a more accurate measurement, not affected by the seating position of the child. The mass is again for CRS with no dummy. The measurements x and z are not taken from the standard perpendicular axes, but as shown in the Figure b.3. All dimensions are in mm.

PHASE 1

Typical production seat      Mass 5.7 Kg      CofG x-135      CofG z-215

PHASE 2

Surrogate Child Restraint System

<u>Shell Pos.</u>	<u>Mass Kg</u>	<u>CofG x</u>	<u>CofG z</u>
a	7.5	138	285
b	"	153	282
c	"	168	279
d	"	129	262
e	"	147	257
f	"	168	252
g	"	118	255
h	"	140	245
i	"	160	235

PHASE 3

<u>Foot Type</u>	<u>Shell Pos.</u>	<u>Mass Kg</u>	<u>CofG x</u>	<u>CofG z</u>
50mm foot	g	7.3	118	240
"	i	7.3	156	230
100mm foot	g	7.6	125	236
"	i	7.6	162	231
3 2 0 x 4 1 0 plate	g	8.5	130	205
"	i	8.5	160	213
4 5 0 x 4 6 0 plate	g	8.4	136	215
"	i	8.4	170	208

PHASE 4

<u>Inclinatio n</u>	<u>Shell Pos.</u>	<u>F o o t Type</u>	<u>Mass Kg</u>	<u>CofG x</u>	<u>CofG z</u>
Recl abt	g	450x460	8.4	148	148
top	i	plate. Bar.	7.3	175	242
"	i	450x460	8.4	155	205
Rec abt	i	plate. Bar.	7.3	151	208
base					

"

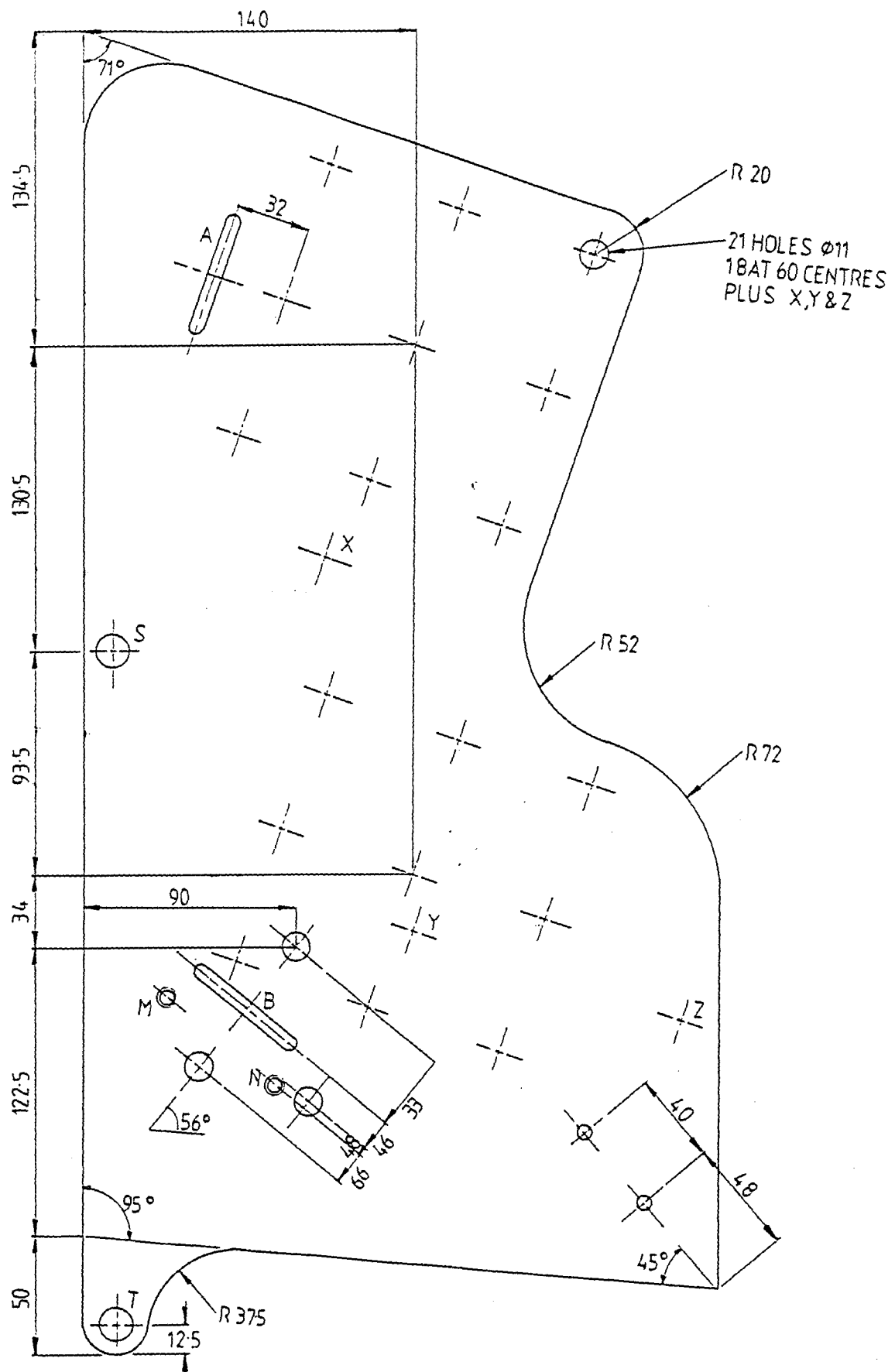
All other tests used one of the combinations above.



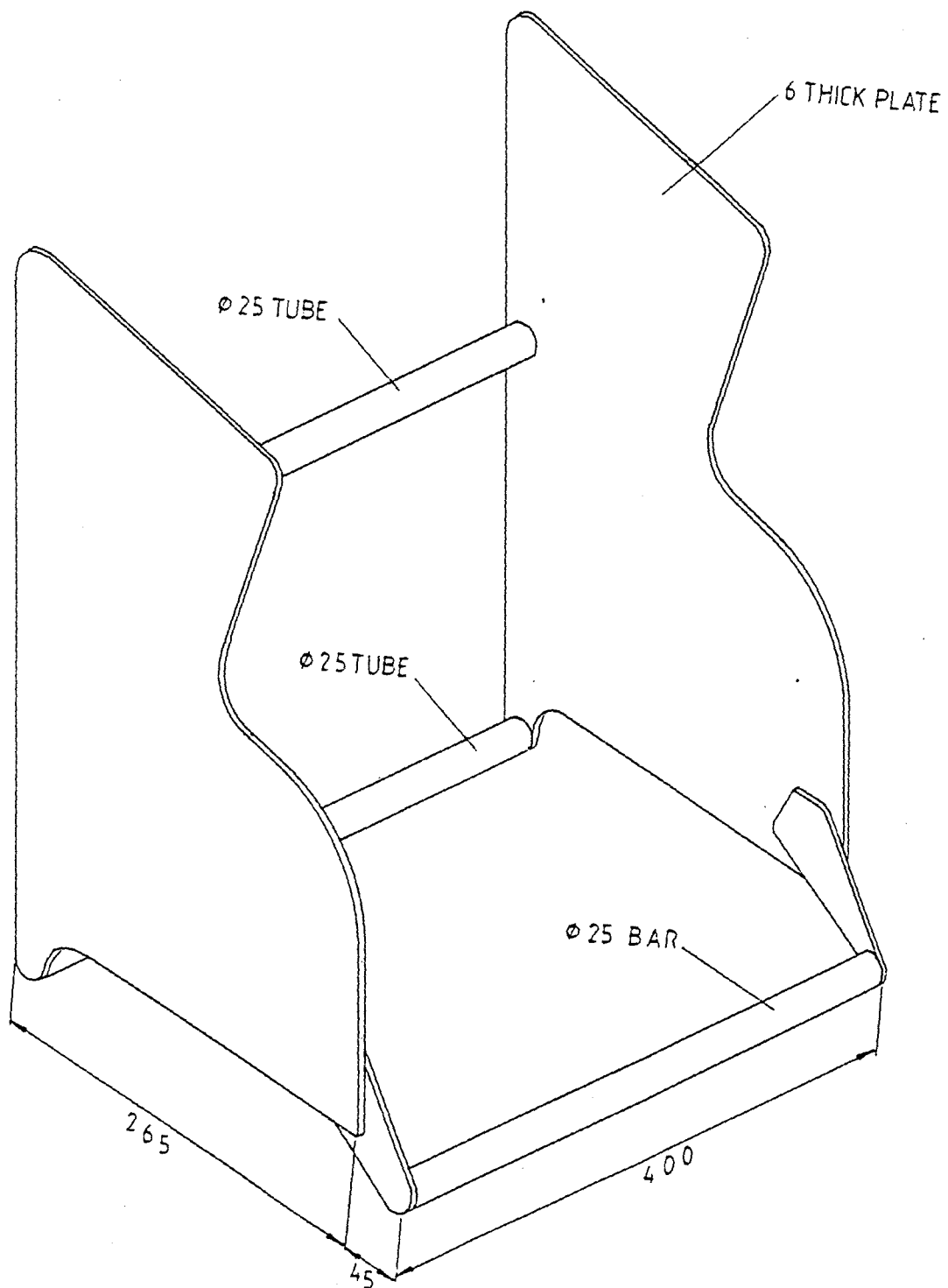
KEY TO Drawing A.1

A & B	-	Webbing routing slots. 55mm long by 5mm wide.
D	-	Standard Adult lap belt surrogate mounting point.
E & F	-	Lower rear and lower front Adult lap belt surrogate mounting points.
M & N	-	Mounting holes for webbing clamp. M6
S & T	-	Dia 13mm holes for frame cross struts.
X	-	Hole for reclining about base. Shell position (i).
Y	-	Hole for reclining about top. Shell position (g).
Z	-	Hole for reclining about top. Shell position (i).

Drawing A.1 Dimensioned Sketch of Surrogate FCS Side Panel  
(See previous page for key)



Drawing A.2 Sketch of Surrogate FCS Frame



[illegible]

APPENDIX B

**APPENDIX B**  
**COMPLETE LISTING OF MADYMO CVS SIMLG2**

```

RUN 1
CRS SIMULATION T1922 NEW CR AXIS
MARK DORN 25 FEB 1991
* ***** *
* GENERAL INITIAL INFO *
* ***** *
0 0.12
0 0.0005 0.001 0.002
0 0.5 0.01 0.1
* ***** *
* DEFINE ADULT CAR SEAT AS INERTIAL SPACE *
* ***** *
INERTIAL SPACE
ECE R44 SEAT
PLANES
0 0.0 -0.400 0.000 0.460 -0.400 0.125 0.460 0.400 0.125 1 0 0 SEATSQUAB
0 0.0 -0.400 -0.140 0.460 -0.400 -0.015 0.460 0.400 -0.015 3 0 0 SEATWELL
0 0.0 -0.400 0.000 0.000 0.400 0.000 -0.160 0.400 0.435 2 0 0 SEATBACK
0 0.460 0.400 -0.015 0.460 -0.400 -0.015 0.460 -0.400 -0.075 3 0 0 SEATFRONTT
0 0.460 0.400 0.125 0.460 -0.400 0.125 0.460 -0.400 -0.015 4 0 0 SEATFRSQ
-999
FUNCTIONS
8
0.0 0.0 0.027 36 0.056 145 0.107 535 0.114 635 0.120 750 0.135 1200 +
0.139 1600
3
0.0 0.0 0.100 2100 0.11 10000
2
0.0 0.0 0.001 10000
2
0.0 0.0 0.09 1000
-999
END INERTIAL SPACE
* ***** *
* DEFINE DUMMY AS SYSTEM 1 *
* SEATED POSITION IS ACHIEVED VIA THE *
* ORIENTATIONS COMMAND ON THE ELLIPSOIDS. *
* ALL OTHER DEFINITIONS REMAIN AS PER DATABASE. *
* ***** *
SYSTEM 1
CHILD P3 SEATED
CONFIGURATION
5 4 3 2 1
7 6 3 2 1
9 8 3 2 1
11 10 1
13 12 1
-999
GEOMETRY
0.000 0.000 0.000 0.013 0.000 -0.059 LOWER TORSO
0.000 0.000 0.000 0.021 0.000 0.103 SPINE
0.000 0.000 0.085 0.015 0.000 0.060 UPPER TORSO
0.015 0.000 0.152 0.000 0.000 0.026 NECK
0.000 0.000 0.056 0.000 0.000 0.067 HEAD
0.015 0.101 0.112 0.000 0.000 -0.079 UPPER ARM LEFT
0.000 0.000 -0.134 0.000 0.000 -0.100 LOWER ARM LEFT
0.015 -0.101 0.112 0.000 0.000 -0.079 UPPER ARM RIGHT
0.000 0.000 -0.134 0.000 0.000 -0.100 LOWER ARM RIGHT
0.022 0.051 -0.068 0.000 0.000 -0.108 UPPER LEG LEFT
0.000 0.000 -0.245 0.000 0.000 -0.140 LOWER LEG LEFT
0.022 -0.051 -0.068 0.000 0.000 -0.108 UPPER LEG RIGHT
0.000 0.000 -0.245 0.000 0.000 -0.140 LOWER LEG RIGHT
-999
INERTIA
2.281 0.011 0.007 0.010
0.490 0.003 0.016 0.017
3.442 0.021 0.017 0.016
0.284 0.001 0.001 0.001
2.625 0.013 0.013 0.015
0.580 0.001 0.001 0.001
0.337 0.001 0.001 0.001
0.580 0.001 0.001 0.001
0.337 0.001 0.001 0.001
1.492 0.014 0.014 0.001
0.845 0.008 0.008 0.001
1.492 0.014 0.014 0.001
0.845 0.008 0.008 0.001
-999

```

## CARDAN JOINTS

10	1	0	0	0	2	0	0	0	3	0	0	0	1.5	1.5	1.25	4.85	4.85	4.85
12	1	0	0	0	4	0	0	0	3	0	0	0	1.5	1.5	1.25	4.85	4.85	4.85
11	5	0	0	0	6	0	0	0	6	0	0	0	1.25	2	1	1.18	0	0
13	5	0	0	0	6	0	0	0	6	0	0	0	1.25	2	1	1.18	0	0
6	0	0	0	0	6	0	0	0	7	0	0	0	0.5	1	1	1.25	1.25	1.25
8	0	0	0	0	6	0	0	0	8	0	0	0	0.5	1	1	1.25	1.25	1.25
7	6	0	0	0	6	0	0	0	9	0	0	0	0.5	1	0.5	0	0	0.34
9	6	0	0	0	6	0	0	0	9	0	0	0	0.5	1	0.5	0	0	0.34
5	10	0	0	0	6	0	0	0	0	0	0	0	0.5	0.5	0.5	1.	0	1.5

-999

## ORIENTATIONS

10	1	1	3	1.5708		
10	10	1	3	1.5708		
12	1	1	3	1.5708		
12	12	1	3	1.5708		
11	10	1	3	1.5708		
11	11	1	3	1.5708		
13	12	1	3	1.5708		
13	13	1	3	1.5708		
5	4	1	3	1.5708		
5	5	1	3	1.5708	1	0.48
6	3	1	1	1.5708	2.	1.5708
6	6	1	1	1.5708	2.	1.5708
8	3	1	1	1.5708	2.	1.5708
8	8	1	1	1.5708	2.	1.5708
7	6	1	2	-1.5708	1.	-1.5708
7	7	1	2	-1.5708	1.	-1.5708
9	8	1	2	-1.5708	1.	-1.5708
9	9	1	2	-1.5708	1.	-1.5708

-999

## FUNCTIONS

5	-2.571	-500	-1.571	0	0	0	1.571	0	2.571	500
5	-1.873	-500	-0.873	0	0	0	0.244	0	1.244	500
5	-1.628	-500	-0.628	0	0	0	0.628	0	1.628	500
5	-1.244	-500	-0.244	0	0	0	0.873	0	1.873	500
4	-1	-500	0	0	2.042	0	3.042	500		
2	-1	-500	1	500						
3	0	0	2.042	0	3.042	500				
3	-3.042	-500	-2.042	0	0	0				
4	-3.426	-500	-2.426	0	0	0	1	500		
5	-1.7	-500	-0.7	0	0	0	0.7	0	1.7	500

-999

## FLEXION TORSION JOINTS

2	1	0	0	0	2	0	0	0	1
3	3	0	0	0	2	0	0	0	1
4	4	0	0	0	0	0	0	0.5	1.

-999

## ORIENTATIONS

4	3	1	2	0.48
---	---	---	---	------

-999

## FUNCTION

6	-1	-500	0	0	0.283	0	0.545	0	0.676	20	1.676	520
4	-1	-32	-0.175	-10	0.175	10	1	32				
6	-1	-500	0	0	0.262	0	0.524	0	0.655	20	1.655	520
5	-1.78	-520	-0.78	-20	0	0	0.78	20	1.78	520		

-999

## ELLIPSOIDS

1	0.060	0.075	0.065	0.015	0.000	-0.070	2	0	0	0	LOWER	TORSO
2	0.065	0.080	0.075	0.015	0.000	0.035	2	0	0	0	SPINE	
3	0.058	0.080	0.088	0.015	0.000	0.070	2	0	0	0	UPPER	TORSO
3	0.029	0.110	0.032	0.015	0.000	0.122	2	0	0	0	SHOULDER	
4	0.030	0.030	0.060	0.000	0.000	0.015	2	0	0	0	NECK	
5	0.080	0.065	0.088	0.014	0.000	0.040	2	0	0	0	HEAD	
6	0.028	0.020	0.093	0.000	0.000	-0.068	2	0	0	0	UPPER	ARM LEFT
7	0.022	0.023	0.100	0.000	0.000	-0.092	2	0	0	0	LOWER	ARM LEFT
8	0.028	0.020	0.093	0.000	0.000	-0.068	2	0	0	0	UPPER	ARM RIGHT
9	0.022	0.023	0.100	0.000	0.000	-0.092	2	0	0	0	LOWER	ARM RIGHT
10	0.040	0.040	0.150	-0.005	0.000	-0.120	2	0	0	0	UPPER	LEG LEFT
11	0.032	0.032	0.130	0.000	0.000	-0.114	2	0	0	0	LOWER	LEG LEFT
11	0.070	0.024	0.015	0.054	0.000	-0.235	2	0	0	0	LEFT	FOOT
12	0.040	0.040	0.150	-0.005	0.000	-0.120	2	0	0	0	UPPER	LEG RIGHT

```

13 0.032 0.032 0.130 0.000 0.000 -0.114 2 0 0 0 LOWER LEG RIGHT
13 0.070 0.024 0.015 0.054 0.000 -0.235 2 0 0 0 RIGHT FOOT
-999
* ***** *
* DEFINE INITIAL POSITION OF TREE STRUCTURE ROOT (ELL 1) *
* DEFINE SEATED POSITION VIA ORIENTATIONS *
* ***** *
INITIAL CONDITIONS
0.037 0.0 0.183
ORIENTATIONS
1 -1 1 2 -0.5236
2 -1 1 2 -0.5236
3 -1 1 2 -0.5236
4 -1 1 2 0.06
5 -1 1 2 0.06
6 -1 1 2 -0.5236
7 -1 1 2 -2.1820
8 -1 1 2 -0.5236
9 -1 1 2 -2.1820
10 -1 1 2 -2.0946
11 -1 1 2 -1.0
12 -1 1 2 -2.0946
13 -1 1 2 -1.0
-999
END SYSTEM 1
* ***** *
* ***** *
* DEFINE SYSTEM 2 - THE CHILD RESTRAINT *
* ***** *
* ***** *
SYSTEM 2
CHILD RESTRAINT
CONFIGURATION
1
-999
GEOMETRY
0.0 0.0 0.0 0.082 0.0 0.244 CRMAS
-999
INERTIA
7.5 0.2 0.23 0.2
-999
ORIENTATIONS
1 1 1 2 0.07
-999
ELLIPSOIDS
1 0.0125 0.200 0.0125 0.000 0.000 0.000 20 0 0 0 REAR BAR
1 0.0125 0.200 0.0125 0.304 0.000 0.000 20 0 0 0 FRONT BAR
-999
PLANES
1 0.069 -0.140 0.059 0.280 -0.140 0.106 0.280 0.140 0.106 +
1 2 2000000 CRSEAT
1 0.069 -0.140 0.059 0.069 0.140 0.059 -0.050 0.140 0.560 +
1 2 2000000 CRBACK
-999
FUNCTIONS
3
0.0 0.0 0.0013 31 0.0102 446
2
0.0 0.0 0.01 50
-999
* INITIAL POSITION OF CR LOWERED INTO SQUAB 50mm
INITIAL CONDITIONS
0.010 0.0 -0.0355
ORIENTATIONS
1 -1 1 2 -0.279
-999
END SYSTEM 2
* ***** *
* FORCE MODELS - FIELDS - BELTS *
* ***** *
FORCE MODELS
ACCELERATION FIELDS
0 0 1 0 2
-999
FUNCTIONS
13
0.0 0.0 0.01 75.6 0.02 98.20 0.03 203.6 0.04 228.8 0.05 243.1 +
0.06 260.5 0.07 238.4 0.08 195.5 0.09 142.7 0.10 45.9 0.11 0.0 0.21 0.0
2
0.0 -9.81 0.21 -9.81
-999
* INITIAL CONTACT FORCE IGNORED (COR=1).

```



```

CONTACT INTERACTIONS
PLANE-ELLIPSE
* SEAT-CR
-1 1 2 1 2 0 0 0 0 0 0.85 0.01 1 0
-1 1 2 2 2 0 0 0 0 0 0.85 0.01 1 0
-1 2 2 1 2 0 0 0 0 0 0.95 0.01 0 0
-1 2 2 2 2 0 0 0 0 0 0.95 0.01 0 0
-1 3 2 1 2 0 0 0 0 0 0.3 0.01 1 0
* SEAT-DUMMY
-1 1 1 12 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 13 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 15 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 16 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 11 2 0 0 0 0 0 0.3 0.01 0 0
-1 1 1 14 2 0 0 0 0 0 0.3 0.01 0 0
-1 5 1 12 2 0 0 0 0 0 0.3 0.01 0 0
-1 5 1 15 2 0 0 0 0 0 0.3 0.01 0 0
* CR-DUMMY
2 1 1 1 2 0 0 0 0 0 0.5 0.01 1 0
2 1 1 11 2 0 0 0 0 0 0.5 0.01 0 0
2 1 1 14 2 0 0 0 0 0 0.5 0.01 0 0
2 2 1 1 2 0 0 0 0 0 0.3 0.01 0 0
2 2 1 2 2 0 0 0 0 0 0.3 0.01 0 0
2 2 1 3 2 0 0 0 0 0 0.3 0.01 0 0
-999
END CONTACT INTERACTIONS
BELTS
-1 0 -0.125 -0.200 -0.125 -1 0 0.000 -0.200 0.000 1 2 1300000 0.04 +
0.1 0.0 0.0 0.1 ADULTLAPINB
-1 0 0.000 -0.200 0.000 2 1 0.067 -0.200 0.162 1 2 1300000 0.04 +
0.1 0.0 0.20 1 ADULTCRINB
2 1 0.067 0.200 0.162 -1 0 0.000 0.200 0.000 1 2 1300000 0.04 +
0.1 0.0 0.20 1 ADULTCROUT
-1 0 0.000 0.200 0.000 -1 0 -0.125 0.200 -0.125 1 2 1300000 0.04 +
0.1 0.0 0.0 1 ADULTLAPPOU
-999
FUNCTIONS
4
0.0 0.0 0.02 3500 0.03 4500 0.105 9000
3
0.0 0.0 0.05 0.0 0.08 2000
-999
* CHILD HARNESS WEBBING STATIC LOAD
BELTS
2 1 -0.022 -0.060 0.438 1 3 0.000 -0.047 0.154 1 2 505100 0.04 +
0.0 -0.31 0.033 0.2 CRTORLEF
1 3 0.059 -0.047 0.114 1 1 0.075 0.000 -0.070 1 2 900000 0.04 +
0.1 0.0 0.06 0.2 CRMIDLEF
1 1 0.015 -0.075 -0.070 2 1 0.121 -0.139 0.125 1 2 1783000 0.04 +
0.1 0.0 0.0 0.2 CRLAPLEF
-999
FUNCTIONS
2
0.0 0.0 0.15 8000
3
0.0 0.0 0.015 0.0 0.025 400
-999
BELTS
2 1 -0.022 0.060 0.438 1 3 0.000 0.047 0.154 1 2 505100 0.04 +
0.0 -0.31 0.033 0.2 CRTORRIGHT
1 3 0.059 0.047 0.114 1 1 0.075 0.000 -0.070 1 2 900000 0.04 +
0.1 0.0 0.06 0.2 CRMIDRIGHT
1 1 0.015 0.075 -0.070 2 1 0.121 0.139 0.125 1 2 1783000 0.04 +
0.1 0.0 0.0 0.2 CRLAPRIGHT
-999
FUNCTIONS
2
0.0 0.0 0.15 8000
3
0.0 0.0 0.015 0.0 0.025 400
-999
END FORCE MODELS
* *****
* OUTPUT FILES / DATA DEFINED *
* *****
OUTPUT CONTROL PARAMETERS
0 1 0.01 0 0
LINDIS
1 5 0.014 0.0 0.128 -1 0 HEAD TOP
1 5 0.014 0.0 0.088 -1 0 HEAD TARG
-999
LINACC
1 3 0.027 0.0 0.050 1 1 1 1 CHEST
1 5 0.000 0.0 0.067 1 1 1 1 HEAD
-999

```

FORCES  
4 2 0  
4 5 0  
4 7 0  
-999  
INJURY PARAMETERS  
AXIAL LOAD  
1 5 4 NECK LOAD  
-999  
3ms VALUE FOR CHEST DECELERATION  
3MS  
1  
-999  
END INJURY PARAMETERS  
END OUTPUT CONTROL  
END INPUT DATA

Figure B.1 Sketch of the 5 Planes Describing the ECE R44 Adult Seat in the MADYMO Model.

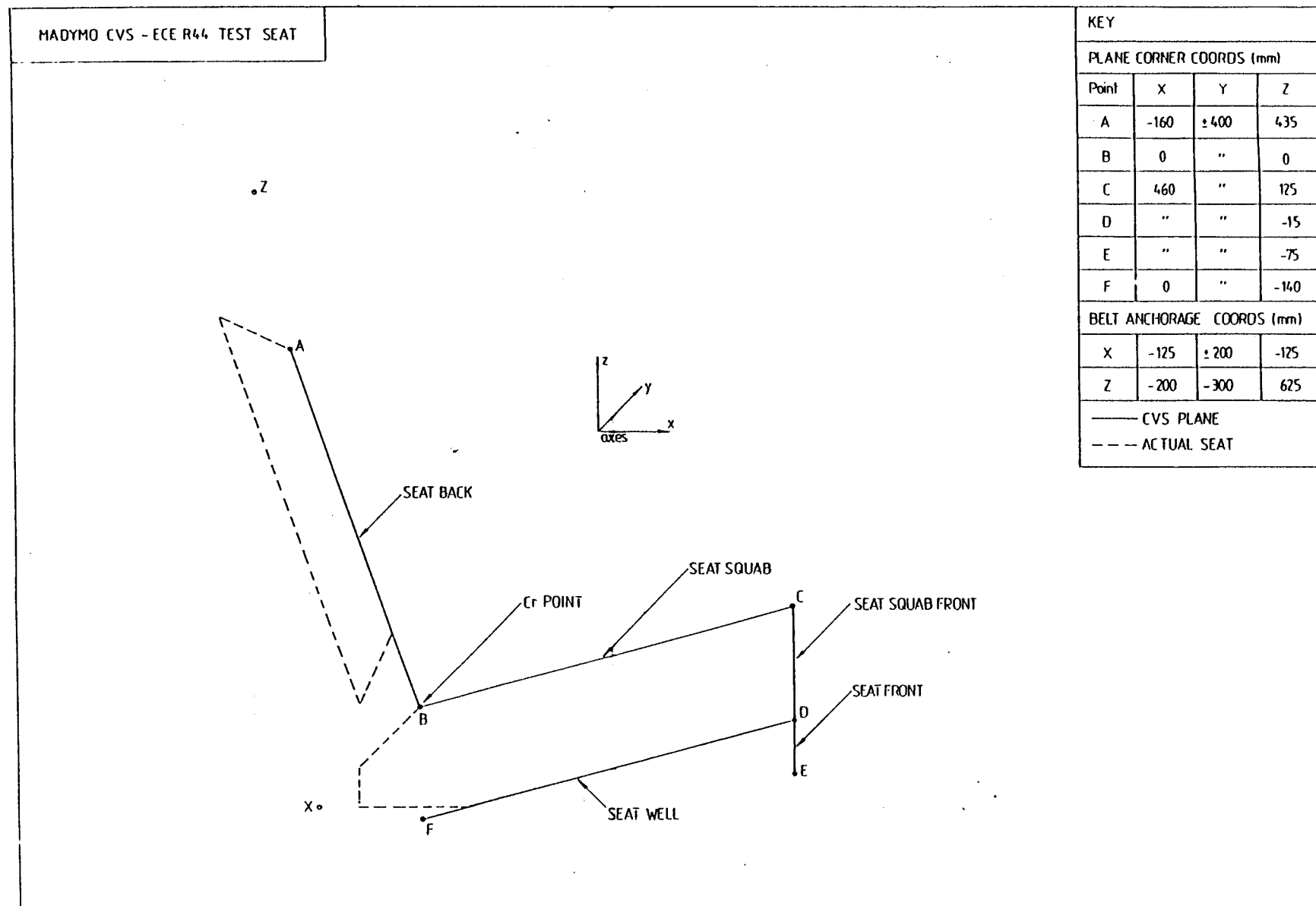
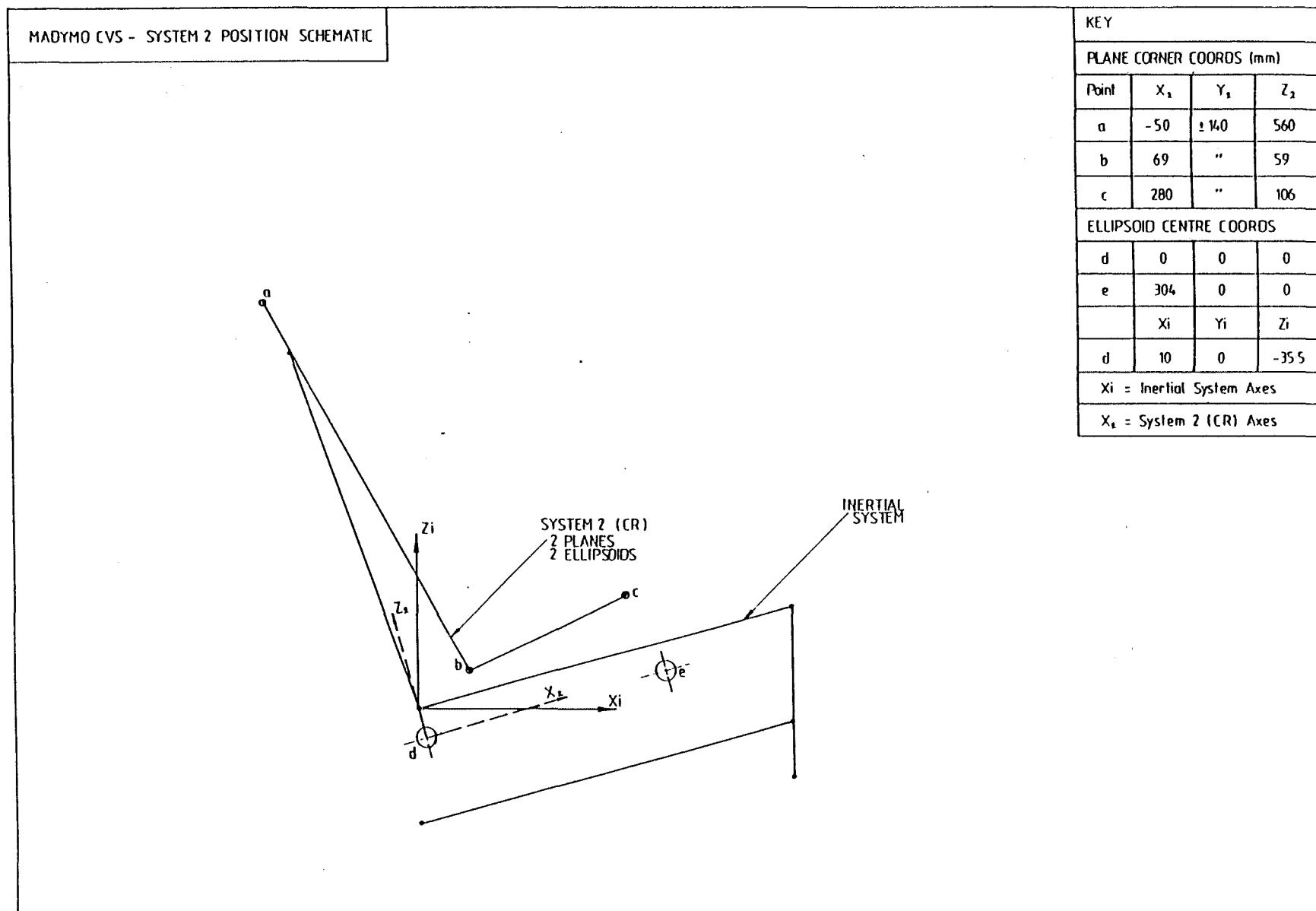


Figure B.2 Sketch of Elements Describing the FCS in the MADYMO Model.



## APPENDIX C

## APPENDIX C

### GATHERING OF DATA FOR CONSTRUCTION OF MADYMO CVS

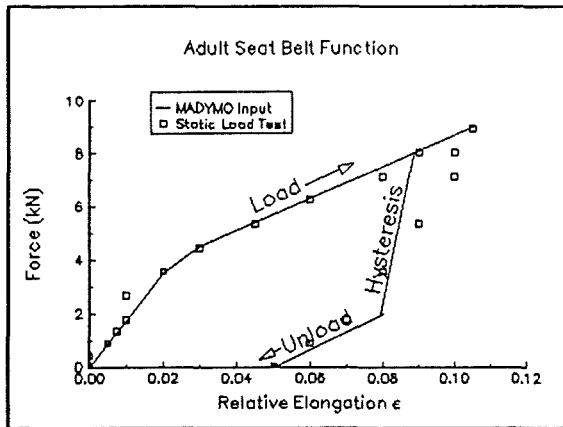
The input data for a MADYMO simulation requires force functions for all of the contact interactions and seat belts. In addition all joints in a system must have a stiffness function defined for all degrees of freedom of that joint. These functions can be estimated if a user has a good knowledge of the subject, but for accurate results the functions should be measured by experiment. The joint stiffnesses for the dummy system were included in the P3 database as supplied by TNO with the MADYMO package. Thus the force functions that were required to construct the model were as follows;

- Dummy to child seat contact
- FCS to adult seat contact
- Adult belt stiffnesses
- Child seat harness stiffness

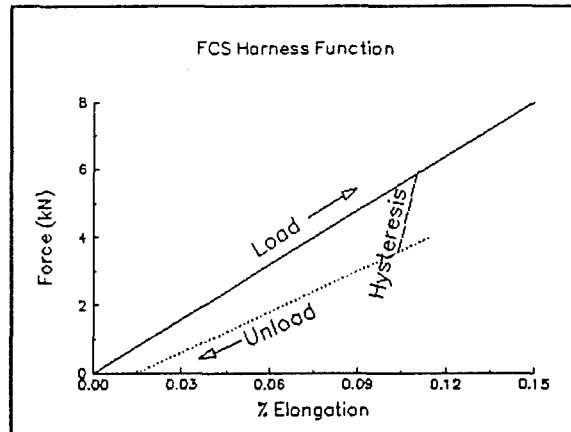
These functions were all measured experimentally in a quasi-static manner. Thus these force functions are subject to some error as the crash test situation is a dynamic environment.

#### C.1 MEASUREMENT OF ADULT SEAT BELT AND CHILD HARNESS STIFFNESS

For measurement of adult seat belt and child harness webbing stiffnesses a standard Avery tensile test machine was used. Measurements of the elongation of a sample of webbing were taken at given load intervals and thus force - extension functions could be plotted. MADYMO requires the extension part of the function to be in terms of relative elongation, ie; elongation relative to original length (Strain). Figure C.1 and Figure C.2 show respectively the stiffness function defined for the adult seat belt and similarly the child restraint harness.



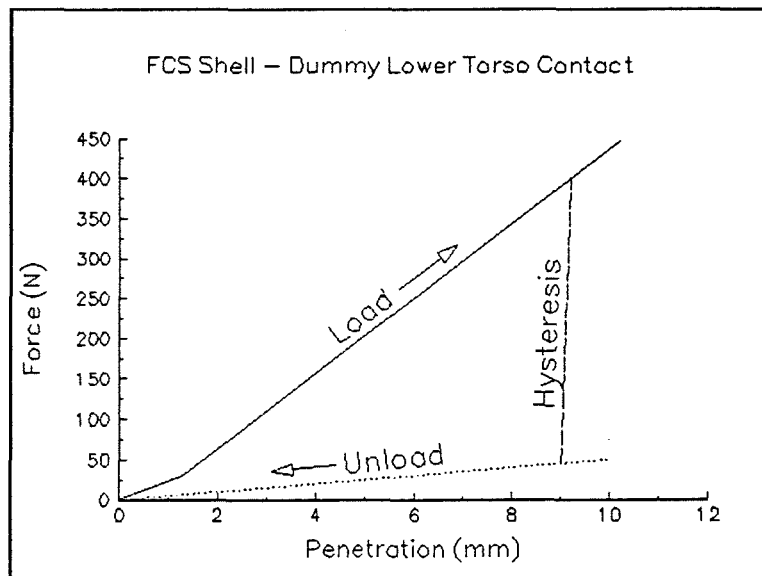
**Figure C.1** Adult belt stiffness function measured for input to MADYMO



**Figure C.2** Child seat harness, webbing stiffness function for input into MADYMO

## C.2 CONTACT FUNCTION FOR THE DUMMY - FRAMED CHILD SEAT INTERFACE

Contact occurs between the dummy and FCS at the lower torso/upper leg and FCS shell interface. In order to gain a reasonably accurate measure of the contact function at this point it was necessary to load (quasi-statically) the



**Figure C.3** Dummy lower torso - FCS shell contact stiffness

FCS shell whilst in place in the child seat frame. This is because the frame provides a rigid support structure for the shell. It was also necessary to load the shell using an object of similar bearing area to the dummy.

Thus the test methodology was to load an area of the shell, where the dummy was thought likely to contact, with static load provided in the form of an increasing number of weights. The deflection of the shell was measured using a dial gauge placed at

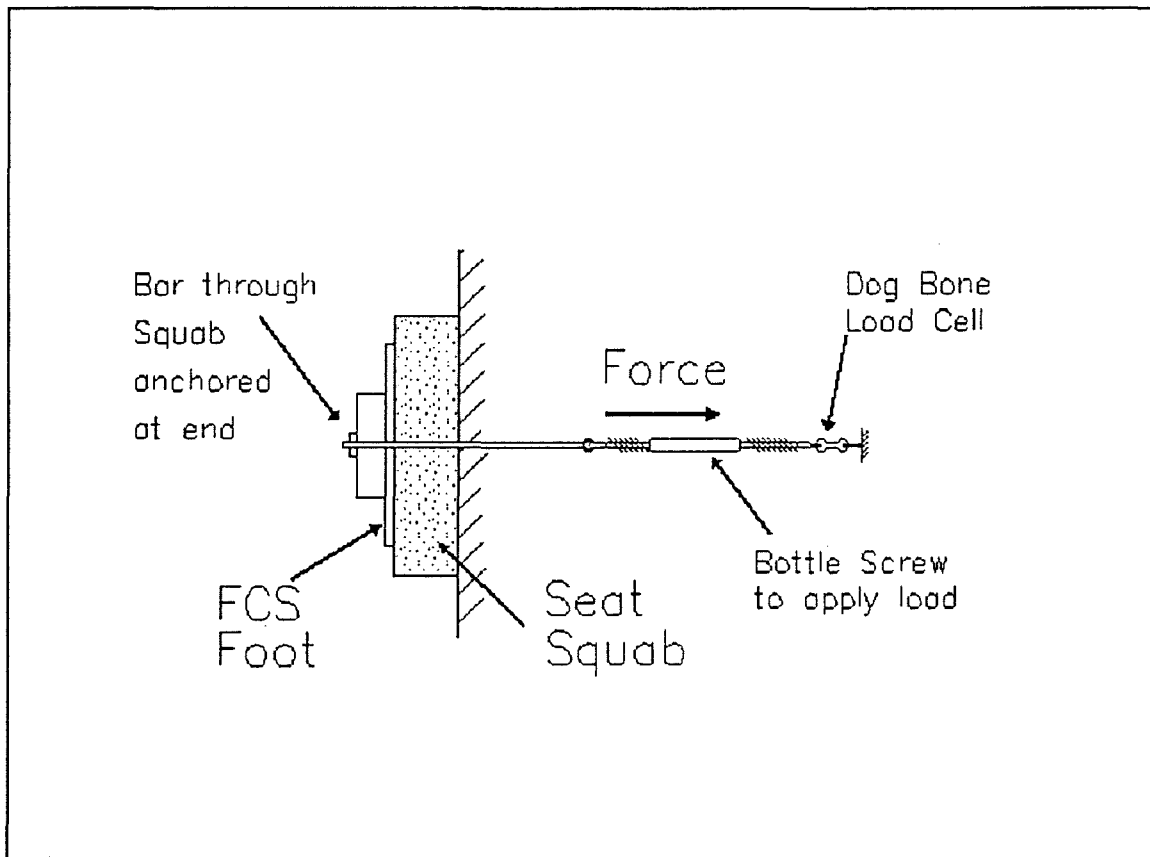
under the shell at the centre of the load. The results of this test are shown in Figure C.3

### C.3 CONTACT FUNCTION FOR THE FCS - TEST SEAT INTERFACE

The FCS depends upon the adult car seat for (1) support in normal use and (2) partial restraint in a crash situation. Thus this contact interaction required quantification as an input for the MADYMO model. The stiffness of this function is dependent upon the bearing area of the foot to seat contact. Thus measurements had to be made for each of the foot areas which were to be simulated.

For measurement of the contact interaction for the surrogate FCS configured with bar feet, weights were loaded into the FCS and the crush of the squab measured. This was not possible for the FCS configured with a large area plate foot. Attempts were made to apply a weight to the plate foot of the FCS whilst it rested horizontally on a seat squab. Unfortunately it was not possible to get accurate measurements of deflection due to uneven depression of the squab. It was also difficult to apply a high load to the foot. Thus the equipment shown in Figure C.4 was designed to overcome these problems. The foot of the FCS was attached rigidly to a bar which passed through a small hole in the squab. The foot was then pulled, by manually tightening a bottle screw, through the squab thickness. The crush of the squab was measured from the movement of the bar, whilst applied load was measured using a 'dog bone' load cell in series with the bottle screw.

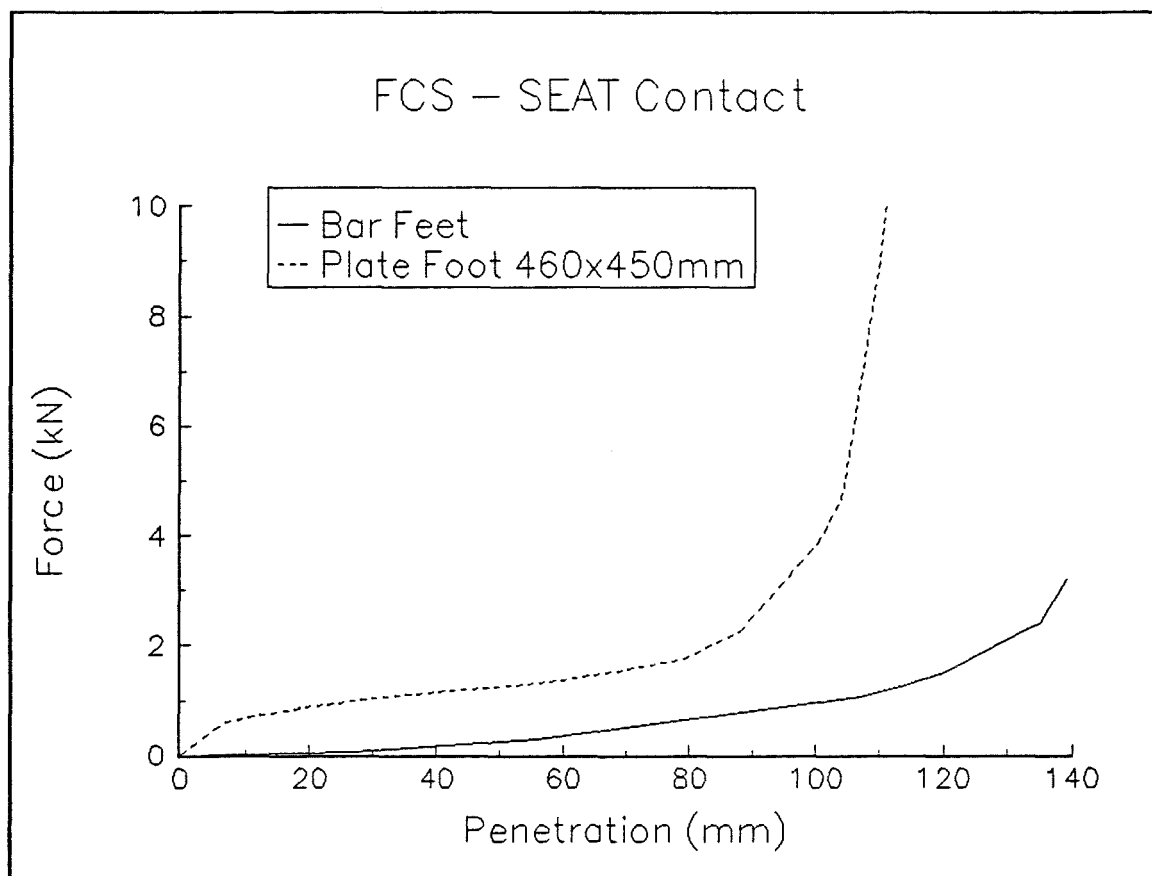




**Figure C.4** Test equipment for FCS Foot - seat squab contact stiffness measurement.

In this manner accurate measurements of FCS foot - squab contact stiffness were possible, with a uniform crush over the bearing area.

The force - penetration factor that was measured for the large plate foot and bar feet are shown in Figure C.5. As would be expected the 450 X 460 mm plate foot induces a higher contact stiffness between foot and squab. This is of course because of the much greater bearing area of that foot which means that a greater area of cushion is being utilised.



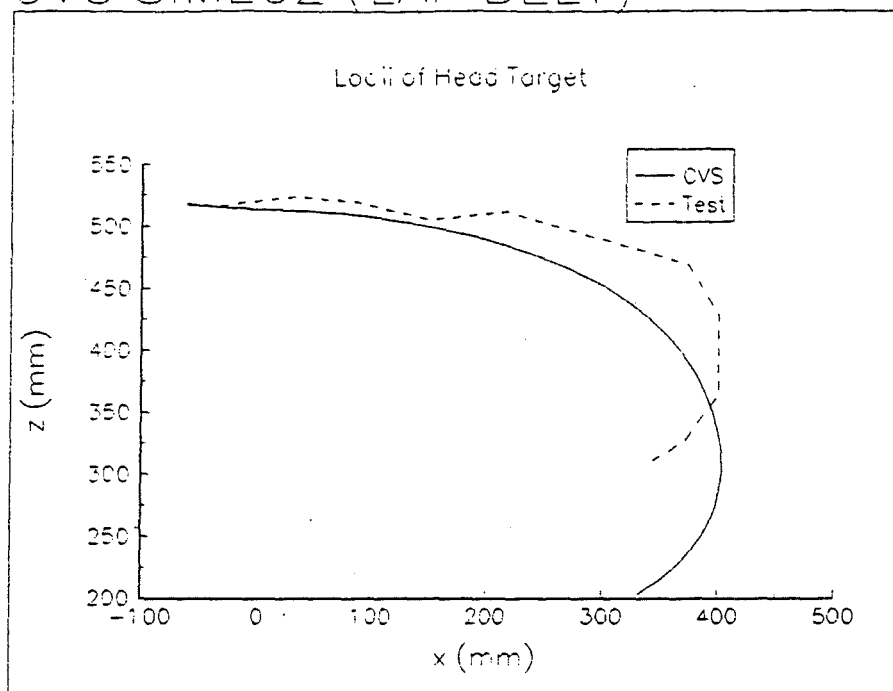
**Figure C.5** FCS foot - seat squab contact function as measured for input into MADYMO

## APPENDIX D

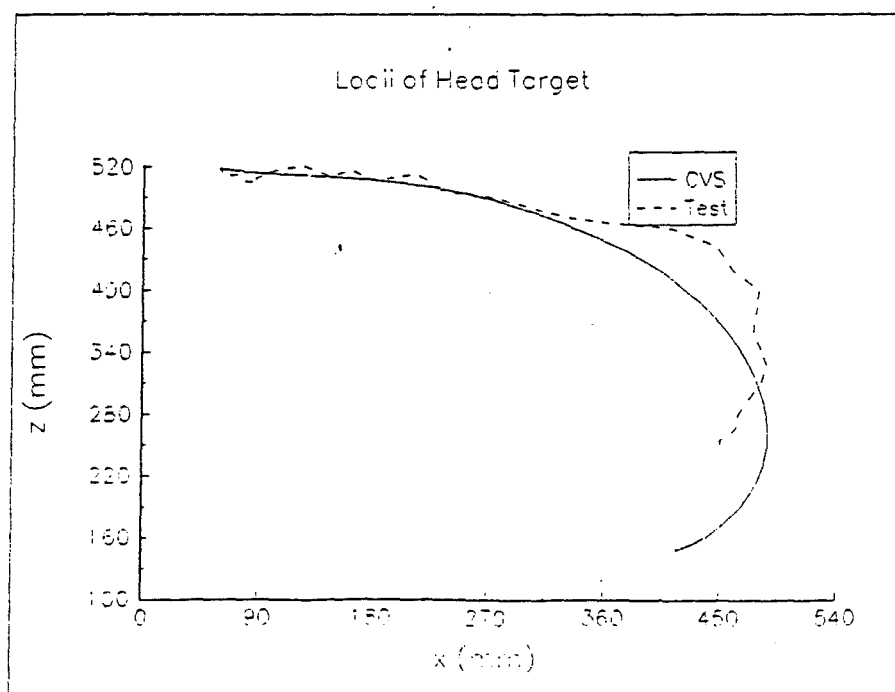
## APPENDIX D

### VALIDATION PLOTS FOR LAP BELT AND 3 POINT BELT SURROGATE FCS MODELS

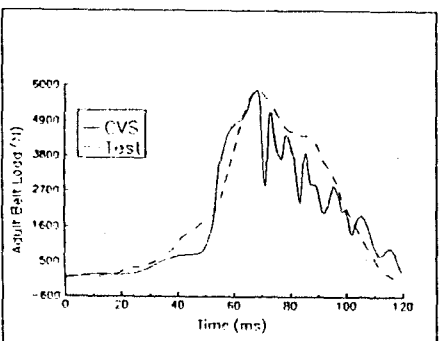
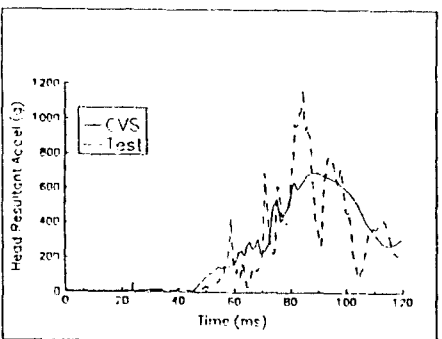
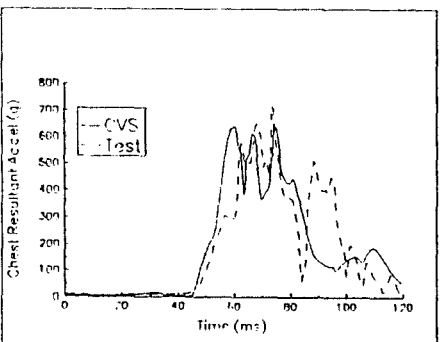
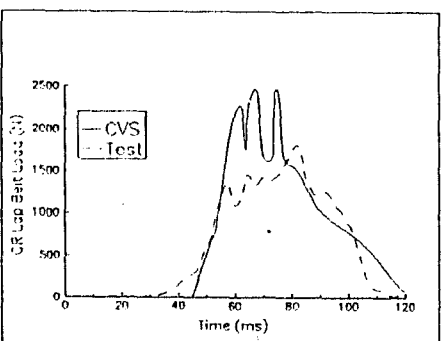
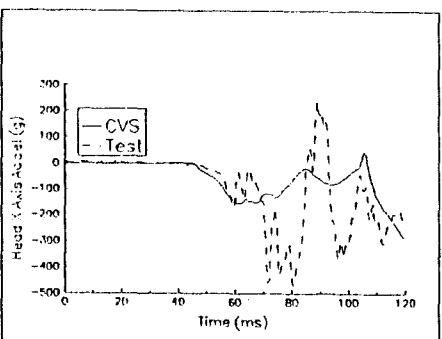
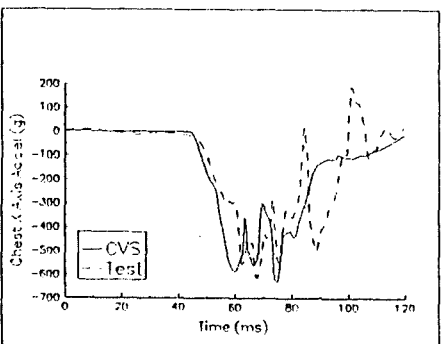
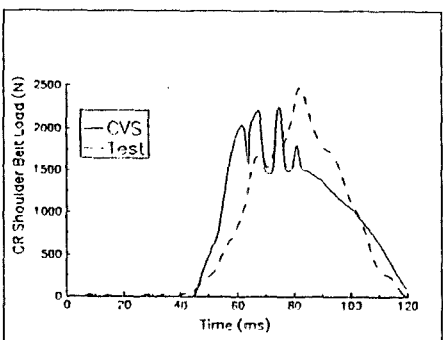
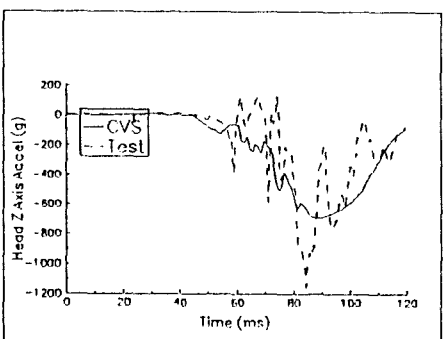
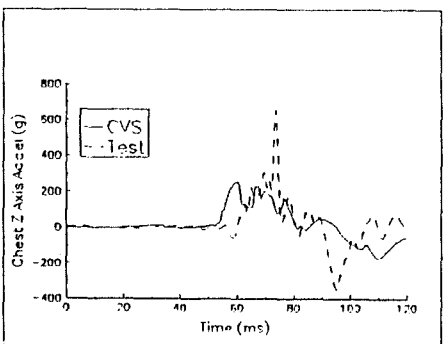
#### HEAD TARGET LOCII COMPARISON CVS SIMLG2 (LAP BELT)



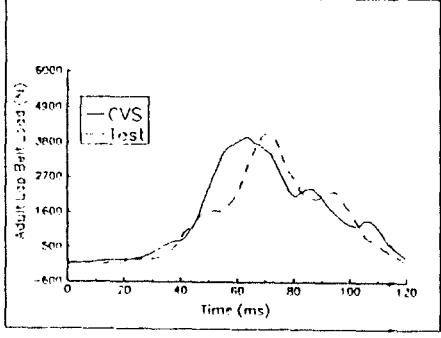
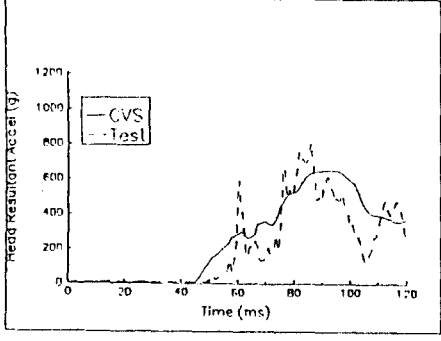
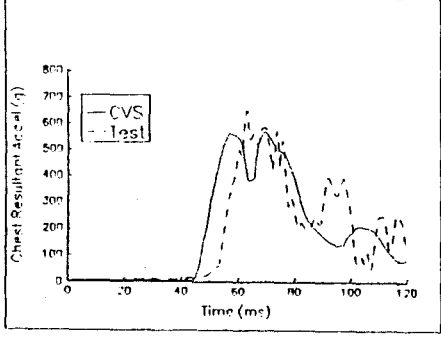
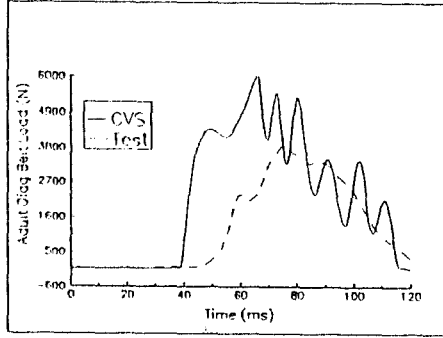
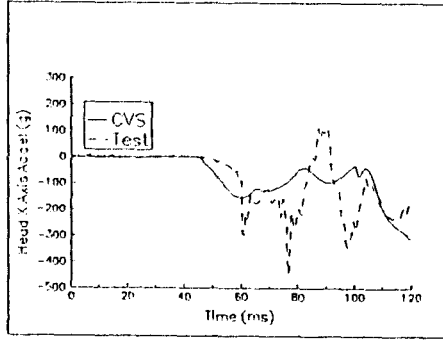
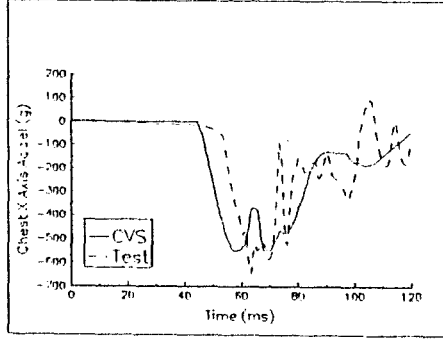
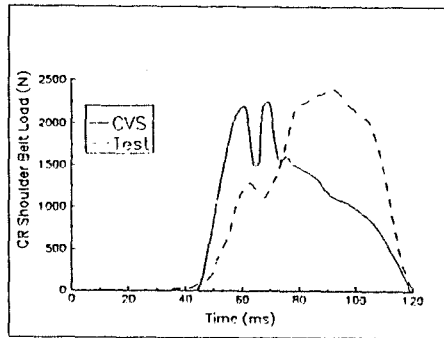
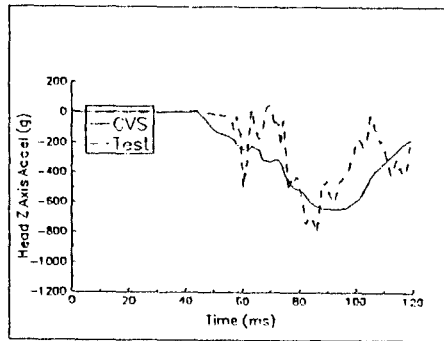
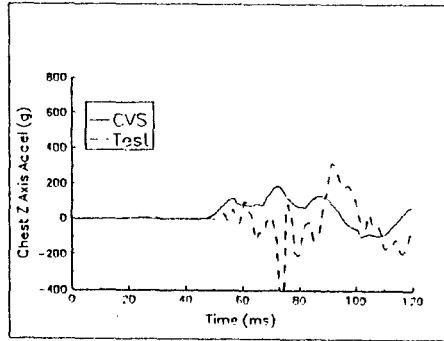
#### CVS SIML-DI2 (3 POINT BELT)



# ACCELERATION & FORCE VALIDATION PLOTS FOR LAP BELT RESTRAINED CVS SIM1G2



# ACCELERATION & FORCE VALIDATION PLOTS FOR 3 POINT BELT RESTRAINED CVS SIML-D12

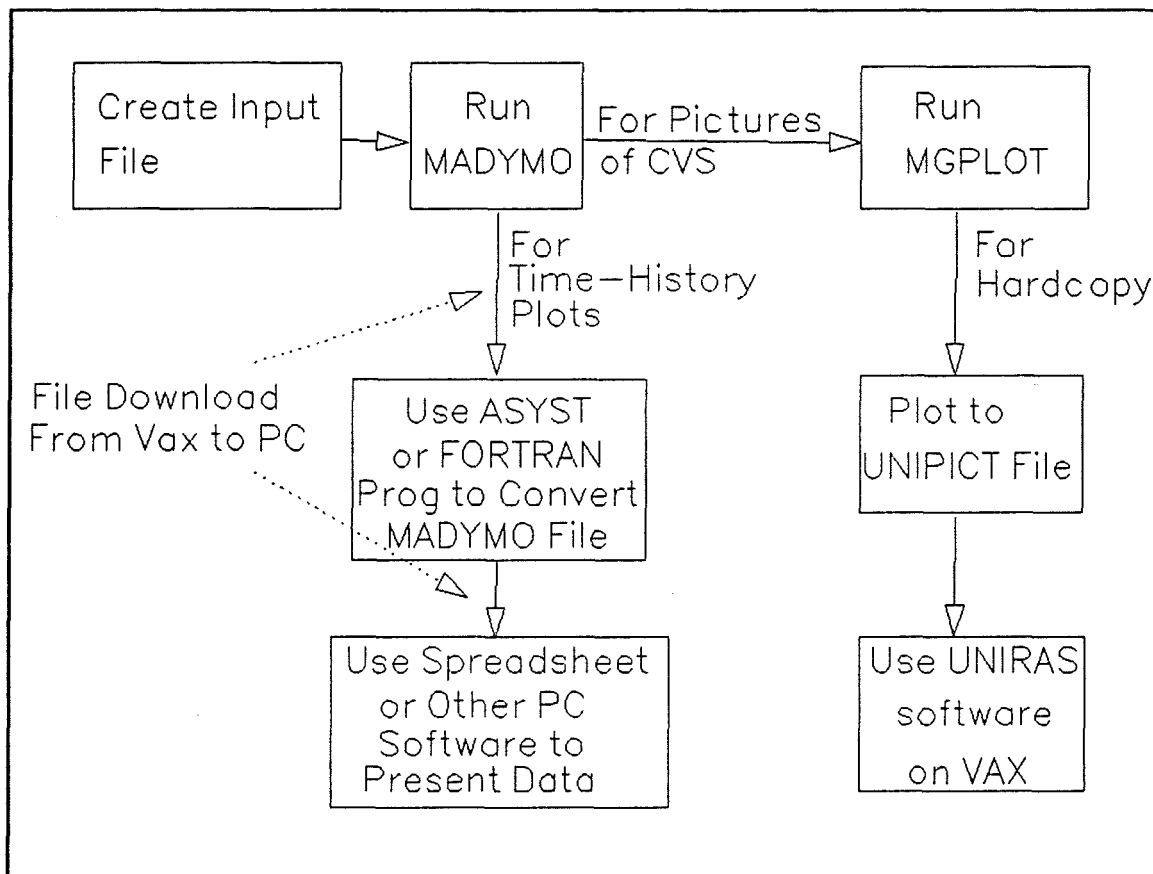


## **APPENDIX E**

## APPENDIX E

### E RUNNING MADYMO AND ASSOCIATED SOFTWARE AT MIDDLESEX UNIVERSITY

MADYMO stands for Mathematical Dynamic Model and was developed by IW-TNO of the Netherlands for the simulation of occupant response in car impacts. It was installed on one of the Middlesex University VAX computers [VAXA]. The VAX system uses the DCL operating system. This addendum deals with the rather complicated task of using MADYMO and necessary associated software. The process is summarised in Figure E.1. In addition to the actual MADYMO programme there are at least 6 other pieces of software that must be used to create the input file (one editor) and postprocess the output data.



**Figure E.1** The process of running madymo and viewing the output

The various stages of MADYMO running and data processing are described in the remainder of this Appendix.



## E.1 RUNNING MADYMO

The following Command files were created to run MADYMO3D:

SUBMAD.COM

MRDMAD.COM

To run MADYMO you type; @SUBMAD SIMNAME, where 'SIMNAME' refers to a directory, of same name, containing a MADYMO input file of name SIMNAME.INP. SUBMAD.COM calls MRDMAD.COM and submits it as a batch job. The listings of these two files are as follows;

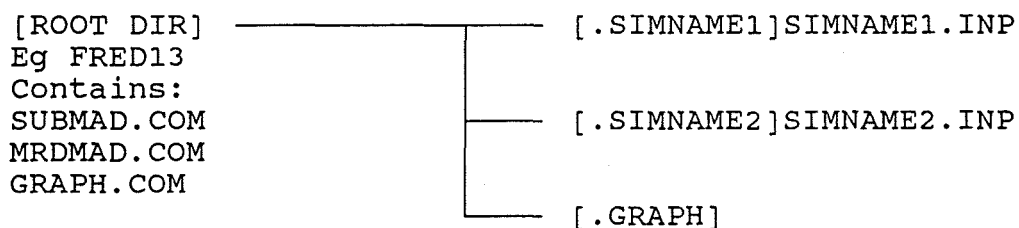
### SUBMAD.COM

```
$ submit /queue=vaxa_batch mrdmad /par=('p1') /notify /noprinter
```

### MRDMAD.COM

```
$ set verify
$!                               Written by Mark Dorn
$!
$!   VMS command file to run MADYMO in batch on USER6:
$!
$ script = "MADYMO3D"
$ oldenvir = f$environment("default")
$!
$ on error then goto err
$!
$ direct = "user5:[mark15.madymo3d." + p1 + "]"
$ set def 'direct
$ testfile = f$search(f$parse(p1, ".inp"), 1)
$ if testfile .eqs. "" then goto nofile
$ datafile = "data.dat"
$ copy/replace 'testfile 'datafile
$!
$ run user6:[madymo.bin]madymo3d
$!
$ goto end
$!
$nofile:
$ write sys$error "%'"script'-f-fnf, input file not found"
$err:
$ write sys$error "%'"script'-f-jab, '"script' job aborted"
$end:
$ delete data.dat;*
$ set def 'oldenvir
```

These COM files were written to organise the input and output files in a correct directory and then run MADYMO. The files required the following directory and file structure:



SUBMAD.COM must be run from the directory in which it is contained, ie; the root directory. The two COM files ran MADYMO from the directory SIMNAME and all output files were then

deposited in this directory. The input file for MADYMO (Eg SIMNAME.INP) can be created using any standard text editor. The COM file MRDMAD.COM copies the input file to a file called DATA.DAT. This is the file in which MADYMO looks for the input data.

A system LOG file is created in the root directory, when the batch job is run. It is called MRDMAD.LOG. This file contains the commands that have been executed and any system error messages Eg. Disk Quota Exceeded.

When MADYMO has been run a file will be created called REPRINT.DAT. This file contains an annotated listing of the input file and any MADYMO error or warning messages that have occurred. All other output files from MADYMO are optional and are specified in the input listing. All the output from MADYMO is in numerical form. MADYMO itself has no capability for producing time-history plots or a visual representation of the crash simulation. Post processors were required to complete this task.

The time taken to run an average simulation varied greatly, depending upon the number of other users on the VAX system. The actual CPU time required for a child restraint simulation of 0.12 seconds equivalent time was 2.5 minutes. The actual elapsed time to complete the simulation varied from 6 minutes to 6 hours. The MADYMO simulation runs were submitted to the VAX batch queue and as such had a low priority for use of CPU time. Therefore if the VAX system was busy then the elapsed time for a simulation increased.

## E.2 GRAPHICAL OUTPUT FROM MADYMO

MADYMO itself only outputs numerical and text files. Thus a postprocessor was required to yield a graphical output. The postprocessor that was used to provide a visual representation of the simulation was called MGLOT. This package was supplied with MADYMO. Another COM file was required to run this program and it was called GRAPH.COM.

To run this programme you had to type; @GRAPH SIMNAME, when in the root directory. This COM file runs MGLOT from a directory called [.GRAPH] which must contain a file called PICTURE.DAT. PICTURE.DAT is a file containing layout information for the MGLOT programme and can be edited interactively during a MGLOT session or with the VAX editor.

When it is run, GRAPH looks for the graphical input file [KINEMA.DAT] in the directory called SIMNAME, it will then copy it to the [.GRAPH] directory and run the MGLOT programme. If the KINEMA.DAT file is not available the programme will not run. *KINEMA.DAT is one of the optional files which must be specified in the MADYMO input file SIMNAME.INP*

### E.2.1 HARDCOPY FROM THE MGLOT PROGRAMME

MGLOT will not produce a HARDCOPY on a printer. It will produce either a screen display or, if you select the plotter, a UNIPICT file, called UNIPICT.DAT, for use in the VAX UNIRAS system.

The MGLOT picture file [UNIPICT.DAT] contains the series of pictures at time intervals as specified by you. Each picture is stored in a block called a segment. This file had to be converted with the UNIRAS picture manager to a file which could be imported

into UNIRAS UNIEDIT 2000. The pictures could then be arranged on a page and annotated. A COM file was written to simplify this procedure. This file was called CONVERT.COM.

To run CONVERT you must have already run GRAPH.COM in the existing VAX session. This is required for two reasons:

- 1) To produce the UNIPICT.DAT file.
- 2) To set up the UNIRAS system.

CONVERT called upon two other files:

- a) UNIPICTCON.COM to do the file conversion and produce a file called UNIPICT.OK
- b) PIC.LOG to arrange the pictures on a UNIEDIT 2000 page.

PIC.LOG was a UNIEDIT 2000 command listing which arranged pictures from the UNIPICT.OK file on a page and annotates the pictures. Once the pictures were displayed in UNIEDIT a hardcopy menu in UNIEDIT package allowed the picture to be directed to a postscript file or to postscript printer.

### E.3 CREATING TIME-HISTORY GRAPHS OF ACCELERATION, FORCE ETC

In order to create time-history plot a seperate postprocessing system was required. The output files from MADYMO are ordinary ASCII text, but are organised in such a way as to make it difficult to use in a spreadsheet or similar software package. The data is arranged in a row format rather than a column format. Thus it was necessary to use a software programme to rearrange the MADYMO data files into a different format. This was achieved in two ways. Firstly by use of a PC based package called ASYST. and secondly by use of a FORTRAN 77 programme on the vax mainframe. The latter programme (MAD-SS.FOR) was more convenient to use and a listing of this programme follows at the end of this

section. Once the file was converted to a more readily accessible format, it could be read into any spreadsheet package. The data could then be presented and analysed at will.

## LISTING OF MAD-SS.FOR

```
PROGRAM CONVERT
INTEGER NPTS, FILTYP, HIGH, MID, C1, C2, POS, GOLABEL
INTEGER P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, NPTSPL, FILNO
REAL INTV, TIME, DA, RNGE, RNGEMS
DIMENSION TIME(1000), DA(50,1000)
CHARACTER*35 RUNNAME, RUNNO*6, DUMPIT*8
CHARACTER*35 POINT(5), ORIEN(10)
WRITE (*,*) ' '
WRITE (*,*) 'A BRILLIANTLY EXECUTED PROGRAMME BY MARK DORN'
WRITE (*,*) ' '
WRITE (*,*) 'WHICH REORGANISES MADYMO OUTPUT DATA'
WRITE (*,*) ' '
WRITE (*,*) 'WHAT IS THE NAME OF THE INPUT FILE ? ENTER...'
WRITE (*,*) ' 1 FOR LINACC.DAT'
WRITE (*,*) ' 2 FOR LINDIS.DAT'
WRITE (*,*) ' 3 FOR FORCES.DAT'
WRITE (*,*) ' 4 FOR LINVEL.DAT'
WRITE (*,*) ' 5 FOR ANGACC.DAT'
WRITE (*,*) ' 6 FOR RELDIS.DAT'
WRITE (*,*) ' 7 FOR PENETR.DAT'
WRITE (*,*) ' 8 FOR TORQU2.DAT'
WRITE (*,*) ' 9 FOR FLEANG.DAT'
WRITE (*,*) '10 FOR REACT1.DAT'
WRITE (*,*) '11 FOR ANY OTHER .DAT'
READ (*,10) FILTYP
IF (FILTYP.GT.10 .OR. FILTYP.LT.1) THEN
    WRITE (*,*) 'FILE TYPE IS NOT SUPPORTED BY THIS PROGRAM !'
    WRITE (*,*) 'GO AND SEE MARK DORN, TALK TO HIM NICELY AND'
    WRITE (*,*) 'HE MAY DO SOMETHING ABOUT IT....TA TA FOR NOW'
    GOTO 999
END IF
WRITE (*,*) 'HOW MANY POINTS ARE RECORDED IN THIS FILE (MAX OF 5)'
READ (*,10) NPTS
IF (NPTS.GT.5) THEN
    WRITE (*,*) 'TOO MANY POINTS !!!'
    WRITE (*,*) 'MAXIMUM OF 5 PER INPUT FILE'
    WRITE (*,*) '.....GET OUT OF HERE.....'
    GOTO 999
END IF
WRITE (*,*) 'WHAT IS THE TIME INTERVAL IN ms ? WITH 1 DP'
READ (*,20) INTV
WRITE (*,*) 'WHAT IS THE TIME RANGE ? 0 TO ...ms'
READ (*,30) RNGEMS
RNGE=RNGEMS/INTV
IF (FILTYP.EQ.1) THEN
    ASSIGN 1 TO GOLABEL
    OPEN(1,FILE='LINACC.DAT',STATUS='OLD')
    OPEN(2,FILE='LINACC.PT1',STATUS='NEW')
    OPEN(3,FILE='LINACC.PT2',STATUS='NEW')
    OPEN(4,FILE='LINACC.PT3',STATUS='NEW')
    OPEN(5,FILE='LINACC.PT4',STATUS='NEW')
    OPEN(6,FILE='LINACC.PT5',STATUS='NEW')
ELSE IF (FILTYP.EQ.2) THEN
    ASSIGN 1 TO GOLABEL
    OPEN(1,FILE='LINDIS.DAT',STATUS='OLD')
    OPEN(2,FILE='LINDIS.PT1',STATUS='NEW')
    OPEN(3,FILE='LINDIS.PT2',STATUS='NEW')
    OPEN(4,FILE='LINDIS.PT3',STATUS='NEW')
    OPEN(5,FILE='LINDIS.PT4',STATUS='NEW')
    OPEN(6,FILE='LINDIS.PT5',STATUS='NEW')
ELSE IF (FILTYP.EQ.3) THEN
    ASSIGN 1 TO GOLABEL
    OPEN(1,FILE='FORCES.DAT',STATUS='OLD')
    OPEN(2,FILE='FORCES.PT1',STATUS='NEW')
    OPEN(3,FILE='FORCES.PT2',STATUS='NEW')
    OPEN(4,FILE='FORCES.PT3',STATUS='NEW')
    OPEN(5,FILE='FORCES.PT4',STATUS='NEW')
    OPEN(6,FILE='FORCES.PT5',STATUS='NEW')
ELSE IF (FILTYP.EQ.4) THEN
    ASSIGN 1 TO GOLABEL
    OPEN(1,FILE='LINVEL.DAT',STATUS='OLD')
    OPEN(2,FILE='LINVEL.PT1',STATUS='NEW')
    OPEN(3,FILE='LINVEL.PT2',STATUS='NEW')
    OPEN(4,FILE='LINVEL.PT3',STATUS='NEW')
    OPEN(5,FILE='LINVEL.PT4',STATUS='NEW')
    OPEN(6,FILE='LINVEL.PT5',STATUS='NEW')
ELSE IF (FILTYP.EQ.5) THEN
    ASSIGN 1 TO GOLABEL
    OPEN(1,FILE='ANGACC.DAT',STATUS='OLD')
    OPEN(2,FILE='ANGACC.PT1',STATUS='NEW')
    OPEN(3,FILE='ANGACC.PT2',STATUS='NEW')
    OPEN(4,FILE='ANGACC.PT3',STATUS='NEW')
    OPEN(5,FILE='ANGACC.PT4',STATUS='NEW')
```

```

OPEN(6,FILE='ANGACC.PT5',STATUS='NEW')
ELSE IF (FILNTP.EQ.6) THEN
    ASSIGN 1 TO GOLABEL
    OPEN(1,FILE='RELDIS.DAT',STATUS='OLD')
    OPEN(2,FILE='RELDIS.PT1',STATUS='NEW')
    OPEN(3,FILE='RELDIS.PT2',STATUS='NEW')
    OPEN(4,FILE='RELDIS.PT3',STATUS='NEW')
    OPEN(5,FILE='RELDIS.PT4',STATUS='NEW')
    OPEN(6,FILE='RELDIS.PT5',STATUS='NEW')
ELSE IF (FILNTP.EQ.7) THEN
    ASSIGN 2 TO GOLABEL
    OPEN(1,FILE='PENETR.DAT',STATUS='OLD')
    OPEN(2,FILE='PENETR.PT1',STATUS='NEW')
    OPEN(3,FILE='PENETR.PT2',STATUS='NEW')
    OPEN(4,FILE='PENETR.PT3',STATUS='NEW')
    OPEN(5,FILE='PENETR.PT4',STATUS='NEW')
    OPEN(6,FILE='PENETR.PT5',STATUS='NEW')
ELSE IF (FILNTP.EQ.8) THEN
    ASSIGN 999 TO GOLABEL
    OPEN(1,FILE='TORQU2.DAT',STATUS='OLD')
    OPEN(2,FILE='TORQU2.PT1',STATUS='NEW')
    OPEN(3,FILE='TORQU2.PT2',STATUS='NEW')
    OPEN(4,FILE='TORQU2.PT3',STATUS='NEW')
    OPEN(5,FILE='TORQU2.PT4',STATUS='NEW')
    OPEN(6,FILE='TORQU2.PT5',STATUS='NEW')
ELSE IF (FILNTP.EQ.9) THEN
    ASSIGN 999 TO GOLABEL
    OPEN(1,FILE='FLEANG.DAT',STATUS='OLD')
    OPEN(2,FILE='FLEANG.PT1',STATUS='NEW')
    OPEN(3,FILE='FLEANG.PT2',STATUS='NEW')
    OPEN(4,FILE='FLEANG.PT3',STATUS='NEW')
    OPEN(5,FILE='FLEANG.PT4',STATUS='NEW')
    OPEN(6,FILE='FLEANG.PT5',STATUS='NEW')
ELSE IF (FILNTP.EQ.10) THEN
    ASSIGN 5 TO GOLABEL
    OPEN(1,FILE='REACT1.DAT',STATUS='OLD')
    OPEN(2,FILE='REACT1.PT1',STATUS='NEW')
    OPEN(3,FILE='REACT1.PT2',STATUS='NEW')
    OPEN(4,FILE='REACT1.PT3',STATUS='NEW')
    OPEN(5,FILE='REACT1.PT4',STATUS='NEW')
    OPEN(6,FILE='REACT1.PT5',STATUS='NEW')
ELSE
    ENDIF
GOTO GOLABEL
1
HIGH=NPTS+7
MID=NPTS+4
DO 99 I=1, HIGH
    C1=I-3
    C2=I-3-NPTS
    IF (I.EQ.1) THEN
        READ(1,40) RUNNAME
    ELSE IF (I.EQ.2) THEN
        READ(1,50) RUNNO
    ELSE IF (I.EQ.3) THEN
        READ(1,*) DUMP
    ELSE IF (I.GT.3 .AND. I.LT.MID) THEN
        READ(1,60) POINT(C1)
    ELSE
        READ(1,60) ORIEN(C2)
    END IF
99
CONTINUE
DO 98 I=1, RNGE
    READ (1,70) TIME(I)
    P1=1
    P2=2
    P3=3
    P4=4
    DO 97 J=1, NPTS
        READ (1,71) DA(P1,I), DA(P2,I), DA(P3,I), DA(P4,I)
        P1=P1+4
        P2=P2+4
        P3=P3+4
        P4=P4+4
97
CONTINUE
98
CONTINUE
NPTSPL=NPTS+1
DO 94 I=1,NPTS
    FILNO=I+1
    WRITE (FILNO,40) RUNNAME
    WRITE (FILNO,61) POINT(I)
    WRITE (FILNO,*) ORIEN(1), ORIEN(2), ORIEN(3), ORIEN(4)
94
CONTINUE
DO 96 I=1,RNGE
    P1=1
    P2=2
    P3=3

```

```

        P4=4
        DO 95 J=2,NPTSPL
        WRITE(J,101) TIME(1), DA(P1,1), DA(P2,1), DA(P3,1), DA(P4,1)
                P1=P1+4
                P2=P2+4
                P3=P3+4
                P4=P4+4
95      CONTINUE
96      CONTINUE
        GOTO 999

2       HIGH=NPTS+5
        MID=NPTS+4
        DO 93 I=1, HIGH
        C1=1-3
        C2=1-3-NPTS
        IF (I.EQ.1) THEN
                READ(1,40) RUNNAME
        ELSE IF (I.EQ.2) THEN
                READ(1,50) RUNNO
        ELSE IF (I.EQ.3) THEN
                READ(1,*) DUMP
        ELSE IF (I.GT.3 .AND. I.LT.MID) THEN
                READ(1,60) POINT(C1)
        ELSE
                READ(1,60) ORIEN(C2)
        END IF
93      CONTINUE
        DO 92 I=1, RNGE
                READ (1,70) TIME(I)
                DO 91 J=1, NPTS
                        READ (1,70) DA(J,I)
91      CONTINUE
92      CONTINUE
        NPTSPL=NPTS+1
        DO 90 I=1,NPTS
        FILNO=I+1
        WRITE (FILNO,40) RUNNAME
        WRITE (FILNO,61) POINT(I)
        WRITE (FILNO,*) ORIEN(I)
90      CONTINUE
        DO 89 I=1,RNGE
        DO 88 J=1,NPTS
        FILNO=I+1
        WRITE(FILNO,102) TIME(I), DA(J,I)
88      CONTINUE
89      CONTINUE

5       HIGH=NPTS+13
        MID=NPTS+4
        DO 87 I=1, HIGH
        C1=1-3
        C2=1-3-NPTS
        IF (I.EQ.1) THEN
                READ(1,40) RUNNAME
        ELSE IF (I.EQ.2) THEN
                READ(1,50) RUNNO
        ELSE IF (I.EQ.3) THEN
                READ(1,*) DUMP
        ELSE IF (I.GT.3 .AND. I.LT.MID) THEN
                READ(1,60) POINT(C1)
        ELSE
                READ(1,60) ORIEN(C2)
        END IF
87      CONTINUE

        DO 85 I=1, RNGE
        READ (1,70) TIME(I)
        P1=1
        P2=2
        P3=3
        P4=4
        P5=5
        P6=6
        P7=7
        P8=8
        P9=9
        P10=10
        DO 86 J=1, NPTS
        READ (1,72) DA(P1,I), DA(P2,I), DA(P3,I), DA(P4,I),
9 DA(P5,I), DA(P6,I), DA(P7,I), DA(P8,I), DA(P9,I), DA(P10,I)
                P1=P1+10
                P2=P2+10
                P3=P3+10
                P4=P4+10
                P5=P5+10

```



```

      P6=P6+10
      P7=P7+10
      P8=P8+10
      P9=P9+10
      P10=P10+10
86      CONTINUE
85      CONTINUE
      NPTSPL=NPTS+1
      DO 84 I=1,NPTS
          FILNO=I+1
          WRITE (FILNO,40) RUNNAME
          WRITE (FILNO,61) POINT(I)
          WRITE (FILNO,*) ORIENT(1), ORIENT(2), ORIENT(3), ORIENT(4),
9 ORIENT(5), ORIENT(6), ORIENT(7), ORIENT(8), ORIENT(9), ORIENT(10)
84      CONTINUE
          DO 83 I=1,RNGE

              P1=1
              P2=2
              P3=3
              P4=4
              P5=5
              P6=6
              P7=7
              P8=8
              P9=9
              P10=10
              DO 82 J=2,NPTSPL
                  WRITE(J,110) TIME(I), DA(P1,I), DA(P2,I), DA(P3,I), DA(P4,I),
9 DA(P5,I), DA(P6,I), DA(P7,I), DA(P8,I), DA(P9,I), DA(P10,I)
                  P1=P1+10
                  P2=P2+10
                  P3=P3+10
                  P4=P4+10
                  P5=P5+10
                  P6=P6+10
                  P7=P7+10
                  P8=P8+10
                  P9=P9+10
                  P10=P10+10

82      CONTINUE
83      CONTINUE
          GOTO 999
10      FORMAT (I2)
20      FORMAT (F4.1)
30      FORMAT (F6.0)
40      FORMAT (A35)
50      FORMAT (A6)
60      FORMAT (A35)
61      FORMAT (A35)
70      FORMAT (E14.6)
71      FORMAT (4E14.6)
72      FORMAT (10E13.6)
101     FORMAT (5F16.5)
110     FORMAT (11F11.2)
102     FORMAT (2F10.5)
999     STOP
      END

```

## APPENDIX F

## APPENDIX F

### F LISTINGS OF CVS AND DATABASES OF NECK MODEL SIMULATIONS

#### F.1 LISTING OF INPUT DATA FOR CVS OF STEP LOAD VALIDATION TEST WITH STANDARD MADYMO P3 DATABASE

RUN 1

STEP RESPONSE SIMULATION TNO P3 DATABASE

MARK DORN 29 MAY 1992

\* \*\*\*\*\* \*

\* GENERAL INITIAL INFO \*

\* \*\*\*\*\* \*

0 0.8

0 0.0005 0.001 0.002

0 0.5 0.01 0.1

SYSTEM 1

CHILD P3

CONFIGURATION

5 4 3 2 1

7 6 3 2 1

9 8 3 2 1

11 10 1

13 12 1

-999

GEOMETRY

0.000 0.000 0.000 0.013 0.000 -0.059 LOWER TORSO

0.000 0.000 0.000 0.021 0.000 0.103 SPINE

0.000 0.000 0.085 0.015 0.000 0.060 UPPER TORSO

0.015 0.000 0.152 0.000 0.000 0.026 NECK

0.000 0.000 0.056 0.000 0.000 0.000 HEAD

0.015 0.101 0.112 0.000 0.000 -0.079 UPPER ARM LEFT

0.000 0.000 -0.134 0.000 0.000 -0.100 LOWER ARM LEFT

0.015 -0.101 0.112 0.000 0.000 -0.079 UPPER ARM RIGHT

0.000 0.000 -0.134 0.000 0.000 -0.100 LOWER ARM RIGHT

0.022 0.051 -0.068 0.000 0.000 -0.108 UPPER LEG LEFT

0.000 0.000 -0.245 0.000 0.000 -0.140 LOWER LEG LEFT

0.022 -0.051 -0.068 0.000 0.000 -0.108 UPPER LEG RIGHT

0.000 0.000 -0.245 0.000 0.000 -0.140 LOWER LEG RIGHT

-999

INERTIA

2.281 0.011 0.007 0.010

0.490 0.003 0.016 0.017

100000 100000 100000 100000

0.284 0.001 0.001 0.001

14.25 0.013 0.013 0.015

0.580 0.001 0.001 0.001

0.337 0.001 0.001 0.001

0.580 0.001 0.001 0.001

0.337 0.001 0.001 0.001

1.492 0.014 0.014 0.001

0.845 0.008 0.008 0.001

1.492 0.014 0.014 0.001

0.845 0.008 0.008 0.001

-999

CARDAN JOINTS

10 1 0 0 0 2 0 0 0 3 0 0 0 1.5 1.5 1.25 4.85 4.85 4.85

12 1 0 0 0 4 0 0 0 3 0 0 0 1.5 1.5 1.25 4.85 4.85 4.85

11 5 0 0 0 6 0 0 0 6 0 0 0 1.25 2 1 1.18 0 0

13 5 0 0 0 6 0 0 0 6 0 0 0 1.25 2 1 1.18 0 0

6 0 0 0 0 6 0 0 0 7 0 0 0 0.5 1 1 1.25 1.25 1.25

8	0	0	0	0	6	0	0	0	8	0	0	0	0.5	1	1	1.25	1.25	1.25
7	6	0	0	0	6	0	0	0	9	0	0	0	0.5	1	0.5	0	0	0.34
9	6	0	0	0	6	0	0	0	9	0	0	0	0.5	1	0.5	0	0	0.34
5	10	0	0	0	6	0	0	0	0	0	0	0	0.5	0.5	0.5	1.	0	1.5

-999

#### ORIENTATIONS

10	1	1	3	1.5708		
10	10	1	3	1.5708		
12	1	1	3	1.5708		
12	12	1	3	1.5708		
11	10	1	3	1.5708		
11	11	1	3	1.5708		
13	12	1	3	1.5708		
13	13	1	3	1.5708		
5	4	1	3	1.5708		
5	5	1	3	1.5708	1	0.48
6	3	1	1	1.5708	2.	1.5708
6	6	1	1	1.5708	2.	1.5708
8	3	1	1	1.5708	2.	1.5708
8	8	1	1	1.5708	2.	1.5708
7	6	1	2	-1.5708	1.	-1.5708
7	7	1	2	-1.5708	1.	-1.5708
9	8	1	2	-1.5708	1.	-1.5708
9	9	1	2	-1.5708	1.	-1.5708

-999

#### FUNCTIONS

5									
-2.571	-500	-1.571	0	0	0	1.571	0	2.571	500
5									
-1.873	-500	-0.873	0	0	0	0.244	0	1.244	500
5									
-1.628	-500	-0.628	0	0	0	0.628	0	1.628	500
5									
-1.244	-500	-0.244	0	0	0	0.873	0	1.873	500
4									
-1	-500	0	0	2.042	0	3.042	500		
2									
-1	-500	1	500						
3									
0	0	2.042	0	3.042	500				
3									
-3.042	-500	-2.042	0	0	0				
4									
-3.426	-500	-2.426	0	0	0	1	500		
5									
-1.7	-500	-0.7	0	0	0	0.7	0	1.7	500

-999

#### FLEXION TORSION JOINTS

2	1	0	0	0	2	0	0	0	1
3	3	0	0	0	2	0	0	0	1
4	4	0	0	0	0	0	0	0	0.5 1.

-999

#### ORIENTATIONS

4	3	1	2	0.48
---	---	---	---	------

-999

#### FUNCTION

6									
-1	-500	0	0	0.283	0	0.545	0	0.676	20 1.676 520
4									
-1	-32	-0.175	-10	0.175	10	1	32		
6									

-1 -500 0 0 0.262 0 0.524 0 0.655 20 1.655 520

5

-1.78 -520 -0.78 -20 0 0 0.78 20 1.78 520

-999

# ELLIPSOIDS

1	0.060	0.075	0.065	0.015	0.000	-0.070	2	0	0	0	LOWER	TORSO
2	0.065	0.080	0.075	0.015	0.000	0.035	2	0	0	0	SPINE	
3	0.058	0.080	0.088	0.015	0.000	0.070	2	0	0	0	UPPER	TORSO
3	0.029	0.110	0.032	0.015	0.000	0.122	2	0	0	0	SHOULDER	
4	0.030	0.030	0.060	0.000	0.000	0.015	2	0	0	0	NECK	
5	0.080	0.065	0.088	0.014	0.000	0.040	2	0	0	0	HEAD	
6	0.028	0.020	0.093	0.000	0.000	-0.068	2	0	0	0	UPPER	ARM LEFT
7	0.022	0.023	0.100	0.000	0.000	-0.092	2	0	0	0	LOWER	ARM LEFT
8	0.028	0.020	0.093	0.000	0.000	-0.068	2	0	0	0	UPPER	ARM RIGHT
9	0.022	0.023	0.100	0.000	0.000	-0.092	2	0	0	0	LOWER	ARM RIGHT
10	0.040	0.040	0.150	-0.005	0.000	-0.120	2	0	0	0	UPPER	LEG LEFT
11	0.032	0.032	0.130	0.000	0.000	-0.114	2	0	0	0	LOWER	LEG LEFT
11	0.070	0.024	0.015	0.054	0.000	-0.235	2	0	0	0	LEFT	FOOT
12	0.040	0.040	0.150	-0.005	0.000	-0.120	2	0	0	0	UPPER	LEG RIGHT
13	0.032	0.032	0.130	0.000	0.000	-0.114	2	0	0	0	LOWER	LEG RIGHT
13	0.070	0.024	0.015	0.054	0.000	-0.235	2	0	0	0	RIGHT	FOOT
5	0.018	0.040	0.018	0.052	0.000	-0.018	2	0	0	0	CHIN	

-999

\* \*\*\*\*\*  
\* DEFINE INITIAL POSITION OF TREE STRUCTURE ROOT (ELL 1) \*  
\* \*\*\*\*\*

# INITIAL CONDITIONS

0.0 0.0 0.0

# ORIENTATIONS

4 -1 1 2 0.48

-999

# END SYSTEM 1

# FORCE MODELS

ACCELERATION FIELDS

1 5 1 0 0

-999

# FUNCTIONS

2

0.0 -9.81 1.0 -9.81

-999

# END FORCE MODELS

\* \*\*\*\*\*  
\* OUTPUT FILES / DATA DEFINED \*  
\* \*\*\*\*\*

# OUTPUT CONTROL PARAMETERS

0 1 0.01 0 0

# LINDIS

1 5 0.0 0.0 0.0 -1 0 HEAD JOINT

1 4 0.0025 0.0 0.176 -1 0 TOP SPINE

-999

# LINACC

1 5 0.000 0.0 0.067 1 1 1 1 HEAD

-999

# END OUTPUT CONTROL

# END INPUT DATA

F.2 LISTING OF INPUT DATA FOR CVS OF STEP LOAD VALIDATION TEST WITH IMPROVED  
MADYMO P3 DATABASE P3MRDIII

RUN 1

STEP TEST SIMULATION P3 DATABASE MRDP3III

MARK DORN JUNE 1992

\* \*\*\*\*\* \*

\* GENERAL INITIAL INFO \*

\* \*\*\*\*\* \*

0 0.8

0 0.0005 0.001 0.002

0 0.5 0.01 0.1

SYSTEM 1

P3 MRDII

CONFIGURATION

9 8 7 6 5 4 3 2 1

11 10 3 2 1

13 12 3 2 1

15 14 1

17 16 1

-999

GEOMETRY

0.000 0.000 0.000 0.013 0.000 -0.059 LOWER TORSO

0.000 0.000 0.000 0.021 0.000 0.103 SPINE

0.000 0.000 0.085 0.015 0.000 0.060 UPPER TORSO

0.015 0.000 0.152 0.000 0.000 0.0093 C5

0.000 0.000 0.010 0.000 0.000 0.0093 C4

0.000 0.000 0.010 0.000 0.000 0.0093 C3

0.000 0.000 0.010 0.000 0.000 0.0093 C2

0.000 0.000 0.010 0.000 0.000 0.0093 C1

\* 0.0125 0.000 0.0168 0.000 0.000 0.067 HEAD

0.0125 0.000 0.0168 0.000 0.000 0.000 HEAD

0.015 0.101 0.112 0.000 0.000 -0.079 UPPER ARM LEFT

0.000 0.000 -0.134 0.000 0.000 -0.100 LOWER ARM LEFT

0.015 -0.101 0.112 0.000 0.000 -0.079 UPPER ARM RIGHT

0.000 0.000 -0.134 0.000 0.000 -0.100 LOWER ARM RIGHT

0.022 0.051 -0.068 0.000 0.000 -0.108 UPPER LEG LEFT

0.000 0.000 -0.245 0.000 0.000 -0.140 LOWER LEG LEFT

0.022 -0.051 -0.068 0.000 0.000 -0.108 UPPER LEG RIGHT

0.000 0.000 -0.245 0.000 0.000 -0.140 LOWER LEG RIGHT

-999

INERTIA

\* 2.281 0.011 0.007 0.010

100000 100000 100000 100000

0.490 0.003 0.016 0.017

\* 3.442 0.021 0.017 0.016

100000 100000 100000 100000

0.0763 0.0005 0.0005 0.0005

0.0657 0.0005 0.0005 0.0005

0.056 0.0005 0.0005 0.0005

0.0471 0.0005 0.0005 0.0005

0.0357 0.0005 0.0005 0.0005

14.25 0.013 0.013 0.015

0.580 0.001 0.001 0.001

0.337 0.001 0.001 0.001

0.580 0.001 0.001 0.001

0.337 0.001 0.001 0.001

1.492 0.014 0.014 0.001

0.845 0.008 0.008 0.001

1.492 0.014 0.014 0.001

0.845 0.008 0.008 0.001

-999

# CARDAN JOINTS

14	1	0	0	0	2	0	0	0	3	0	0	0	1.5	1.5	1.25	4.85	4.85	4.85
16	1	0	0	0	4	0	0	0	3	0	0	0	1.5	1.5	1.25	4.85	4.85	4.85
15	5	0	0	0	6	0	0	0	6	0	0	0	1.25	2	1	1.18	0	0
17	5	0	0	0	6	0	0	0	6	0	0	0	1.25	2	1	1.18	0	0
10	0	0	0	0	6	0	0	0	7	0	0	0	0.5	1	1	1.25	1.25	1.25
12	0	0	0	0	6	0	0	0	8	0	0	0	0.5	1	1	1.25	1.25	1.25
11	6	0	0	0	6	0	0	0	9	0	0	0	0.5	1	0.5	0	0	0.34
13	6	0	0	0	6	0	0	0	9	0	0	0	0.5	1	0.5	0	0	0.34
9	10	0	0	0	6	0	0	0	0	0	0	0	0.5	0.5	0.5	1.	0	1.5

-999

# ORIENTATIONS

14	1	1	3	1.5708		
14	14	1	3	1.5708		
16	1	1	3	1.5708		
16	16	1	3	1.5708		
15	14	1	3	1.5708		
15	15	1	3	1.5708		
17	16	1	3	1.5708		
17	17	1	3	1.5708		
9	8	1	3	1.5708		
9	9	1	3	1.5708	1.	0.48
10	3	1	1	1.5708	2.	1.5708
10	10	1	1	1.5708	2.	1.5708
12	3	1	1	1.5708	2.	1.5708
12	12	1	1	1.5708	2.	1.5708
11	10	1	2	-1.5708	1.	-1.5708
11	11	1	2	-1.5708	1.	-1.5708
13	12	1	2	-1.5708	1.	-1.5708
13	13	1	2	-1.5708	1.	-1.5708

-999

# FUNCTIONS

5	-2.571	-500	-1.571	0	0	0	1.571	0	2.571	500
5	-1.873	-500	-0.873	0	0	0	0.244	0	1.244	500
5	-1.628	-500	-0.628	0	0	0	0.628	0	1.628	500
5	-1.244	-500	-0.244	0	0	0	0.873	0	1.873	500
4	-1	-500	0	0	2.042	0	3.042	500		
2	-1	-500	1	500						
3	0	0	2.042	0	3.042	500				
3	-3.042	-500	-2.042	0	0	0				
4	-3.426	-500	-2.426	0	0	0	1	500		
5	-1.7	-500	-0.7	0	0	0	0.7	0	1.7	500

-999

# FLEXION TORSION JOINTS

2	1	0	0	0	2	0	0	0	1
3	3	0	0	0	2	0	0	0	1
4	4	0	0	0	0	0	0	0	0.3 1.
5	4	0	0	0	0	0	0	0	0.3 1.
6	4	0	0	0	0	0	0	0	0.3 1.

7 4 0 0 0 0 0 0 0 0.3 1.  
8 4 0 0 0 0 0 0 0 0.3 1.

-999

# FUNCTIONS

4

0 0 0.545 0 0.676 20 1.676 520

4

-1 -32 -0.175 -10 0.175 10 1 32

4

0 0 0.524 0 0.655 20 1.655 520

5

\* -1.78 750 -0.78 25 0 0 0.78 25 1.78 750

-1.78 936 -0.78 36 0 0 0.78 36 1.78 936

-999

# ELLIPSOIDS

1 0.060 0.075 0.065 0.015 0.000 -0.070 2 0 0 0 LOWER TORSO

2 0.065 0.080 0.075 0.015 0.000 0.035 2 0 0 0 SPINE

3 0.058 0.080 0.088 0.015 0.000 0.070 2 0 0 0 UPPER TORSO

3 0.029 0.110 0.032 0.015 0.000 0.122 2 0 0 0 SHOULDER

3 0.035 0.035 0.0051 0.015 0.000 0.1511 16 1 0 0 EC6

4 0.0325 0.0325 0.0051 0.000 0.000 0.0093 16 2 0 0 EC5

5 0.030 0.030 0.0051 0.000 0.000 0.0093 16 3 0 0 EC4

6 0.0275 0.0275 0.0051 0.000 0.000 0.0093 16 4 0 0 EC3

7 0.025 0.025 0.0051 0.000 0.000 0.0093 16 5 0 0 EC2

8 0.0225 0.030 0.0125 0.000 0.000 0.0168 16 6 0 0 ATLAS

9 0.080 0.065 0.088 0.014 0.000 0.040 2 0 0 0 HEAD

10 0.028 0.020 0.093 0.000 0.000 -0.068 2 0 0 0 UPPER ARM LEFT

11 0.022 0.023 0.100 0.000 0.000 -0.092 2 0 0 0 LOWER ARM LEFT

12 0.028 0.020 0.093 0.000 0.000 -0.068 2 0 0 0 UPPER ARM RIGHT

13 0.022 0.023 0.100 0.000 0.000 -0.092 2 0 0 0 LOWER ARM RIGHT

14 0.040 0.040 0.150 -0.005 0.000 -0.120 2 0 0 0 UPPER LEG LEFT

15 0.032 0.032 0.130 0.000 0.000 -0.114 2 0 0 0 LOWER LEG LEFT

15 0.070 0.024 0.015 0.054 0.000 -0.235 2 0 0 0 LEFT FOOT

16 0.040 0.040 0.150 -0.005 0.000 -0.120 2 0 0 0 UPPER LEG RIGHT

17 0.032 0.032 0.130 0.000 0.000 -0.114 2 0 0 0 LOWER LEG RIGHT

17 0.070 0.024 0.015 0.054 0.000 -0.235 2 0 0 0 RIGHT FOOT

9 0.018 0.040 0.018 0.052 0.000 -0.018 2 0 0 0 CHIN

3 0.030 0.080 0.044 0.045 0.000 0.114 4 0 0 0 COLLAR BONE

-999

# FUNCTIONS

2

0.0 0.0 0.004 439

2

0.0 0.0 0.004 365

2

0.0 0.0 0.004 297

2

0.0 0.0 0.004 234

2

0.0 0.0 0.004 175

2

0.0 0.0 0.001 10000

-999

\* \*\*\*\*\* \*

\* DEFINE INITIAL POSITION OF TREE STRUCTURE ROOT (ELL 1) \*

\* DEFINE SEATED POSITION VIA ORIENTATIONS \*

\* \*\*\*\*\* \*

# INITIAL CONDITIONS

0.0 0.0 0.00

END SYSTEM 1



```

FORCE MODELS
ACCELERATION FIELDS
1 9 1 0 0
-999
FUNCTIONS
2
0.0 -9.81 1.0 -9.81
-999
END FORCE MODELS
* ***** *
* OUTPUT FILES / DATA DEFINED *
* ***** *
OUTPUT CONTROL PARAMETERS
0 1 0.01 0 0
LINDIS
1 9 0.0 0.0 0.0 -1 0 HEAD JOINT
1 8 0.0 0.0 0.0443 -1 0 TOP SPINE
-999
LINACC
1 9 0.000 0.0 0.067 1 1 1 1 HEAD
-999
END OUTPUT CONTROL
END INPUT DATA

```

## APPENDIX G

## TABLES OF MISUSE DATA AS OBSERVED BY RSEL STAFF

## Misuse of Child Restraints

Infant Carriers	Restraint Number							Totals	Totals %
	1	2	3	4	5	6	7		
Misused ?	1	1	1	0	1	1	1	6	86
Type of Misuse									
Slack in Harness	1	1	1				1	4	67
Slack in Adult Belt			1					1	17
Harness Misroute								0	0
Adult Belt Misroute			1			1		2	33
No Crotch Strap								0	0
Harness Maladjusted		1					1	2	33
Inappropriate Device			1					1	17
Other					1			1	17
CR Name	LOV	B2W	B30	B30	B30	B2W	B2W		

Total Misuse		
CR Type	Misused	Correct
Infant	86	14
Framed	93	7
2/4 Point	92	8
Booster	9	91

## Notes

Totals % is percentage of a misuse type as a function of No. misused

Harness maladjustment generally describes wrong position of buckle

Framed CR	Restraint Number																														Totals	Totals %
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		
Misused ?	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	28	93
Type of Misuse																																
Slack in Harness	1	1		1		1	1				1	1	1	1	1	1		1	1							1	1				15	54
Slack in Adult Belt		1	1	1	1	1	1			1			1	1							1					1	1			1	13	46
Harness Misroute			1		1				1							1				1							1				5	18
Adult Belt Misroute	1								1		1				1	1	1	1	1		1	1	1	1					1		12	46
No Crotch Strap																																
Harness Maladjusted	1	1		1	1	1					1	1	1		1							1	1	1	1	1		1		1	16	57
Inappropriate Device																															0	0
Other														1			1												1		3	11
CR Name	B30	BM2	B30	SD2	M2S	SDR	BR	B2W	B30	BR	M	B2W	SD2	B30	B2W	B2W	B2W	B2W	B2W	M2S	M2S	BR	B2W	B2W	BT2	BR	COS	B2W	BR	SDR		

4 Point/2 Point	Restraint Number													Totals	Totals %
	1	2	3	4	5	6	7	8	9	10	11	12	13		
Misused ?	1	1	1	1	1	1	1	1	1	1	1	0	1	12	92
Type of Misuse															
Slack in Harness	1	1			1			1		1				5	42
Slack in Anchorages	1	1	1			1			1	1				6	50
Harness Misroute	1													1	8
Anchor Strap Misroute	1											1		3	25
No Crotch Strap							1							1	8
Harness Maladjusted				1	1				1	1	1			5	42
Inappropriate Device		1	1	1									1	4	33
Other											1			1	8
CR Name	B30	DS	BR1	B20	M2S	B30	DS	DS	DS	BR	SD	BR	BB70		

Booster Seat/Cushion	Restraint Number											Totals	Totals %
	1	2	3	4	5	6	7	8	9	10	11		
Misused ?	0	0	1	0	0	0	0	0	0	0	0	1	9
Type of Misuse													
Slack in Adult Belt												0	0
Adult Belt Misroute			1									1	100
Inappropriate Device												0	0
CR Name	DUO	WIN	DUO	BTX	KNG	KOM	KID	BTX	UNK	BTX	KOM		

## Key to Name Abbreviations

B20 KL B20 2 Point  
 B30 KL B30 Super Traveller Frame Seat  
 B2W Britax 2 Way Frame Seat  
 BB70 KL 4 Point  
 BM2 Britax Mark 2 Frame Seat  
 BR Britax Recliner Frame Seat  
 BR4 Britax Four Point  
 BT2 Boots 2 Way Frame Seat  
 BTX Britax Booster Cushion  
 COS Cosatto Go Safe Frame Seat  
 DS Kangol Dreamseat 2 Point  
 DUO Kangol Duoseat Booster Seat

KID Kiddy 100 SE Booster Cushion  
 KNG Kangol Booster Cushion  
 KOM KL B2R Kombi-Seat Booster Seat  
 LOV GM Love Seat Infant Carrier  
 M Mothercare Frame seat  
 M2S Mothercare 2 Stage Frame Seat  
 SD Kangol Super Dreamseat Frame Seat  
 SD2 Kangol Super Dreamseat Mark 2  
 SDR Kangol Super Dreamseat Recliner  
 UNK Unknown  
 WIN Winner Booster Seat